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A Lifting Surface Computer Code with Jet-in-Crossflow Interference Effects

Volume I - Theoretical Description

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Volume I - Theoretical Description

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SYMBOLS

c	configuration chord length
C_p	pressure coefficient
ΔC_p	interference pressure coefficient
d, D, D_j	jet diameter
L	aerodynamic lift
ΔL	interference aerodynamic lift
M	aerodynamic pitching moment
ΔM_j	interference pitching moment about the jet center
$\Delta M_{.25}$	interference pitching moment about the configuration quarter chord
R	jet-to-crossflow velocity ratio
$R_{D/Sp}$	ratio of the jet diameter to the control point spacing
x, y, z	axes of the jet coordinate system, see Figure 1
X, Y, Z	axes of the panel code coordinate system, see Figure 2
XJCT, YJCT, ZJCT	location of the jet center in the panel code coordinate center
U_j	jet exit velocity
U_∞	freestream velocity
α	model angle of attack
β	model yaw angle
γ	angle between the jet z-axis and the panel code Z-axis, jet roll angle

δ	jet injection angle
τ_j	isentropic jet thrust

SUMMARY

A method is proposed to combine a numerical description of a jet in a crossflow with a lifting surface panel code to calculate the jet/aerodynamic-surface interference effects on a V/STOL aircraft. An iterative technique is suggested that starts with a model for the properties of a jet/flat plate configuration and modifies these properties based on the flow field calculated for the configuration of interest. The method would estimate the pressures, forces, and moments on an aircraft out of ground effect.

A first-order approximation to the method suggested is developed and applied to two simple configurations. The first-order approximation is a non-iterative procedure which does not allow for interactions between multiple jets in a crossflow and also does not account for the influence of lifting surfaces on the jet properties. The jet/flat plate model utilized in the examples presented is restricted to a uniform round jet injected perpendicularly into a uniform crossflow for a range of jet-to-crossflow velocity ratios from three to ten. Numerical results for a streamlined body of revolution and a symmetrical airfoil are presented. The numerical results show that there is good agreement between experimental and model calculated surface pressure data for the body of revolution and the non-lifting wing, but indicate the need for iterative techniques for handling the interactions between lifting surfaces and a jet in a crossflow.

This report is divided into two volumes. The first volume is a theoretical description of the computer code developed. The second volume is a detailed Users Guide for the computer code.

SECTION I
INTRODUCTION

Vertical or short take-off and landing (V/STOL) aircraft traditionally supplement aerodynamic lift with high energy lift jets. While the use of lift jets is efficient when viewed from a static standpoint, they create adverse aerodynamic interference effects when used to supplement wing-generated lift during forward flight. When lift jets are used during forward flight they are called jets in a crossflow, and the mode of flight is termed transitional flight. The adverse interference effects result from the viscous mixing of the lift jet fluid with the crossflow fluid. The major adverse effects are a lift loss and a nose-up pitching moment. These effects increase in severity with increasing crossflow velocity.

As defined herein a jet in crossflow refers to the qualitative features of a jet injected into a crossflow. The terminology jet/aerodynamic-surface refers to a jet in crossflow issuing from an arbitrary aerodynamic surface. A jet/flat plate refers to a jet in crossflow issuing from a flat plate configuration.

Modern high speed computers, through the use of panel codes, can be used to solve for the flow field on or about a conventional aircraft for the conditions of attached flow. A panel code is a program which solves a linear partial differential equation numerically, by approximating the configuration surface with a set of panels, on which unknown singularity strengths are defined. The application of boundary conditions at a

discrete set of points, such as the panel centroids, generates a system of linear algebraic equations relating the unknown singularity strengths to the flow at the panel centroids. The equations are then solved for the singularity strengths, which once known, provide the properties of the flow field about the configuration.[1-3]

Although existing panel codes can be used to solve the flow field about a conventional aircraft, they fail to predict the adverse interference effects on a V/STOL aircraft in transitional flight. One method for predicting the jet-in-crossflow interference effects on a V/STOL aircraft is that of Kuhn.[4] The method developed by Kuhn applies empirical corrections to the aerodynamic coefficients for aircraft without jets in crossflow. Kuhn's method estimates the integrated interference effects; lift loss, and pitching moment. There are methods currently under development which will combine programs for predicting jet/flat plate interference effects with panel codes.[5]

Most jet-in-crossflow models in use today predict the flow field due to the properties of a jet/flat plate model. This is because the development of a <u>general</u> jet/aerodynamic-surface model is too complex. Two programs in use today, which estimate jet/flat plate interference effects, use potential flow singularities to model the jet properties. The first, developed by Wooler et al.,[6] combines a distribution of sinks and doublets along a calculated jet path to obtain the velocity field due to the jet interference. The second program was originated by Dietz[7] in his masters thesis and later developed to its present form by Fearn.[8] The Dietz/Fearn model assumes two contrarotating vortices to be the dominant flow feature, thus the vortex properties are the major influence in the jet interference effects. A non-potential flow program

has been developed by Adler and Baron,[9] which uses an integral control volume method to represent the axial flow internal to the jet plume.

A jet/aerodynamic-surface modeling method is proposed in this report which combines a jet/flat plate model with a low-order panel code to model the flow field about a V/STOL aircraft when operating out of ground effect. The method proposed should be capable of accounting for all interactions between jets in crossflow and a lifting surface configuration. A jet/aerodynamic-surface model is presented, based on the proposed method, which accounts for the influence of jets in crossflow on the lifting surface, but does not account for the influence of the lifting surface on the jet properties. The model presented combines the jet/flat plate model of Fearn[8] with a low-order panel code developed by Analytical Methods Incorporated.[10]

Section II of this report discusses modeling methods, including panel codes and jet-in-crossflow codes. Sections III and IV deal with the mechanics of combining the two computer codes used and the testing of the resultant computer code. Section V presents the results for the configuration studies and concludes Volume 1 of this report. Volume 2 of this report presents a detailed Users Guide for the WBWJAS computer code developed in Volume 1.

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SECTION II
MODELING METHODS

Low-Order Panel Codes

A panel code is a program which solves numerically the linear partial differential equation describing potential flow about a surface. It does this by approximating the surface with a set of panels on which singularities of unknown strength are defined. The common singularities are sources to describe a non-lifting surface, and in addition, doublets or vortices, to describe a lifting surface. A low-order panel code is a program in which the singularity strength distribution is piecewise constant over the configuration. Higher-order panel codes require the singularity strength distribution to fit linear, quadratic or higher-order equations.

A generic wing-body configuration is shown in Figure 1, which is a reproduction from reference 11. The figure shows source panels defining the configuration shape; the panel control points are shown as dots at the panel centroids. The vortex system is shown in the wings, with trailing vortices to represent the wake region downstream of the wings. Each singularity shown has associated with it a perturbation velocity flow field. The vector sum of all perturbation velocities and the freestream velocity describe the flow field of a particular configuration. Analytical expressions for the perturbation velocity flow field induced by a constant source distribution on an arbitrary panel are given by Hess and Smith.[1] Similarly, the velocity field

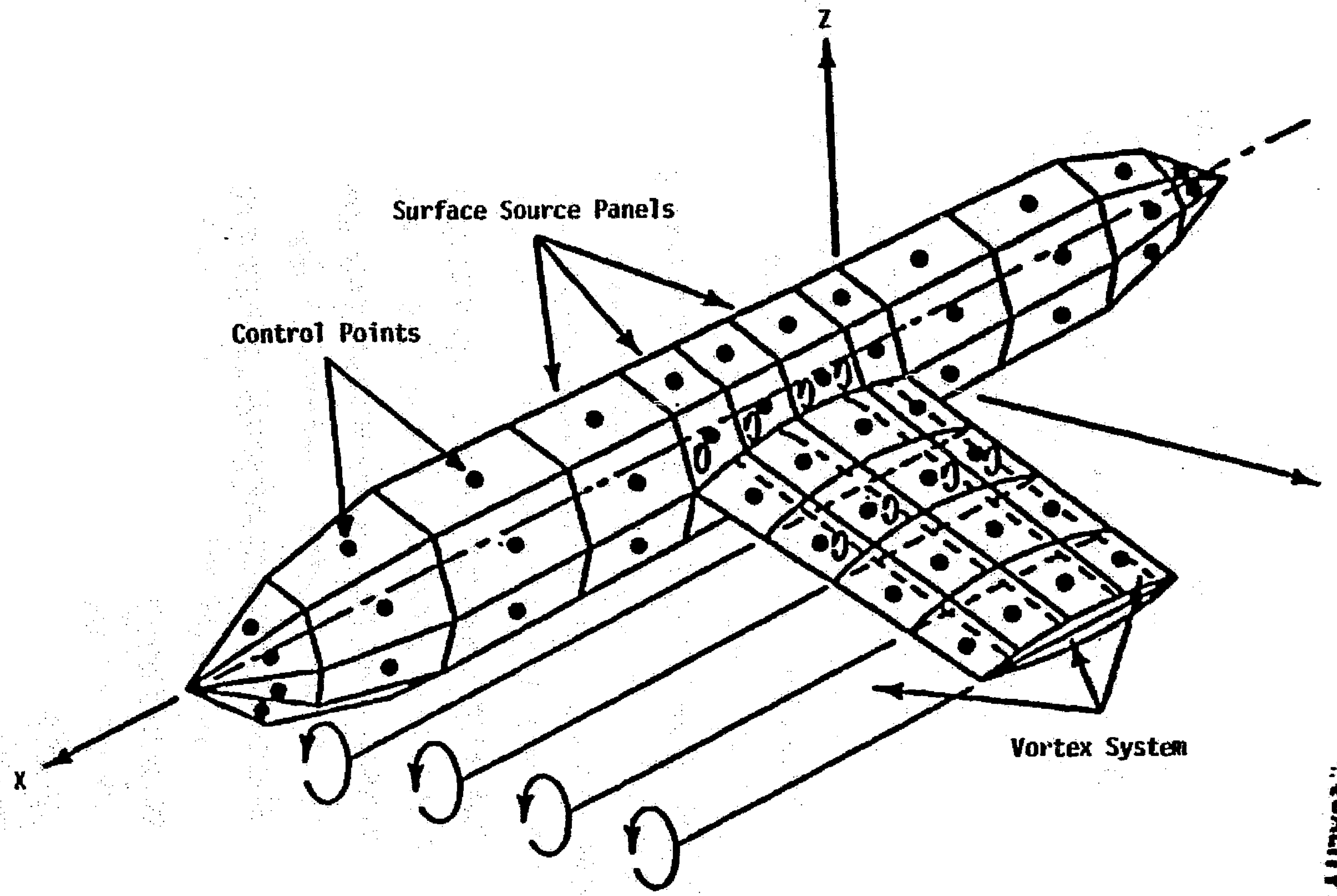

Figure 1. - Source and Vortex Panel Arrangements on a Wing-Body Configuration (reference 11).

induced by the elements of a vortex distribution are given by Woodward[2] and by Rubbert et al.[3]

The perturbation velocities are used to calculate the coefficients of a system of linear algebraic equations, relating the magnitude of the velocities at the panel control points, to the unknown singularity strengths. The singularity strengths, which produce the perturbation velocities necessary to satisfy the boundary conditions on each panel, are determined by solving the system of linear algebraic equations. With the singularity strengths known, the velocity field is determined and the pressure coefficients calculated using Bernoulli's equation. The pressure distribution is integrated numerically over the configuration to yield the forces and moments on the configuration.

The panel method chosen for this project is a low-order panel code composed by Dvorak, Maskew, and Woodward.[10] The method is known by the acronym WBABL, which stands for Wing Body Aerodynamic program with Boundary Layer solutions. The major reasons for choosing the WBABL panel code are its accessibility and the availability of knowledgeable program users at the NASA Ames Research Center, where this project originated.

Jet-in-Crossflow Codes

A jet/aerodynamic-surface model should be capable of predicting the interference effects on an aerodynamic configuration due to the flow field associated with a jet in a crossflow. As a prelude to discussing jet/aerodynamic-surface models, a qualitative description of the flow field is in order.

Description of the Flow Field

Based on extensive experimental investigations of a subsonic jet injected into a subsonic crossflow, a qualitative description of the flow field can be made. This description of the flow field follows that presented by Fearn.[8] The characteristics of a jet in a crossflow described here apply mainly to a round jet, injected perpendicularly into the crossflow, from a flat plate. Although the characteristics given below are for a particular jet/aerodynamic-surface configuration, they are characteristic of the general jet-in-crossflow flow field.

Jet core. For a relatively short distance from the jet exit plane, the core flow of the jet is characterized by slow changes in flow properties such as velocity profile and turbulent intensity. For a submerged jet, with no crossflow, the jet core is conical in shape and extends approximately six jet diameters from the jet exit plane[12] before it is eroded into a highly turbulent flow. When the jet is injected into a crossflow, the length of the jet core is found to decrease with decreasing jet-to-crossflow velocity ratio.

Shear layer. The boundary between the jet and the crossflow can be considered a shear layer between the high and low energy flows. This shear layer is thin near the jet exit, but rapidly thickens as the jet core diffuses. It is thought that this shear layer can be represented by a region of concentrated vorticity,[13] the diffusion of which can be used to describe the flow field of the jet core with no crossflow. In the presence of a crossflow the shear layer (vortex structure) is distorted as well as diffused by the crossflow. The distortion of the shear layer is thought to be the origin of the pair of contrarotating vortices which are characteristic of the jet-in-crossflow flow field.

Contrarotating vortex pair. The dominant feature in the jet-in-crossflow flow field is a pair of diffuse contrarotating vortices. The vortex pair has been observed to start near the jet exit and extend far downstream.[14] The diffuse vortex pair is deflected downstream along curved paths. These paths lie on either side of the plane of flow symmetry and are located on the concave side of the jet centerline.[14,15] As the contrarotating vortices are swept downstream they diffuse rapidly until their core radius is approximately equivalent to the half spacing between the vortex centers. The diffusion of vorticity between the two vortices results in a decrease in the strength of each vortex. As an indication of the dominance of the contrarotating vortices as a flow feature, the vortex pair has been observed as far as 1000 jet diameters downstream from the jet orifice.[16]

Jet plume. The jet plume is readily observed by flow visualization techniques such as smoke injection.[17] The deflection and decay of the initial jet can be detected by velocity measurements in the jet plume. The curve that traces the locations of the maximum jet speed, from the terminus of jet core through cross sections of the jet plume, is called the jet centerline. The location of the jet centerline can be determined to a point where the local maximum of the jet velocity is indistinguishable from the freestream velocity. The extent of the jet centerline has been found to be fifteen to twenty jet diameters downstream of the jet exit for the instrumentation used in the tests of Fearn and Weston[14] (i.e., yaw/pitch probes).

Wake. Complicating the flow field near the jet exit is a wake region. This wake is clearly visible in oil smear studies on a flat plate.[18] The wake region begins just downstream of the jet core and is

a result of a separation of the crossflow as it flows around the jet core.

Most of the features described above are shown in Figure 2. The figure is representative of a jet in a crossflow issuing from a flat plate at a ninety degree injection angle and a jet-to-crossflow velocity ratio (R) of eight. The stippled area represents the observed smoke plume, within which the relative locations of the jet centerline and vortex curve are shown. The vortex curve is a projection of one of the vortex paths onto the symmetry plane. The diffuse contrarotating vortex pair is illustrated in a cross section to the jet plume, and relative positions of the jet core and flat plate wake region are shown. Also shown in Figure 2 are the coordinate axes used to describe the jet properties.

Jet/Flat Plate Models

A jet/aerodynamic-surface model should provide the perturbation velocities at a point of interest due to the combined influences of the jet/aerodynamic-surface structure. Existing modeling techniques for transitional flight consist largely of empirically derived models, using potential flow singularities to account for the complex flow structure. Three jet/aerodynamic-surface models are discussed here, all use a flat plate as the aerodynamic-surface configuration.

The first model discussed, developed by Wooler et al.,[6] combines distributions of sinks and doublets along the calculated jet path to obtain the velocity field due to the jet interference. As shown in Figure 3, the sinks are uniformly distributed along an axis normal to the freestream, and account for the entrainment of the jet. Their strength, which varies with the distance from the jet, is dependent upon

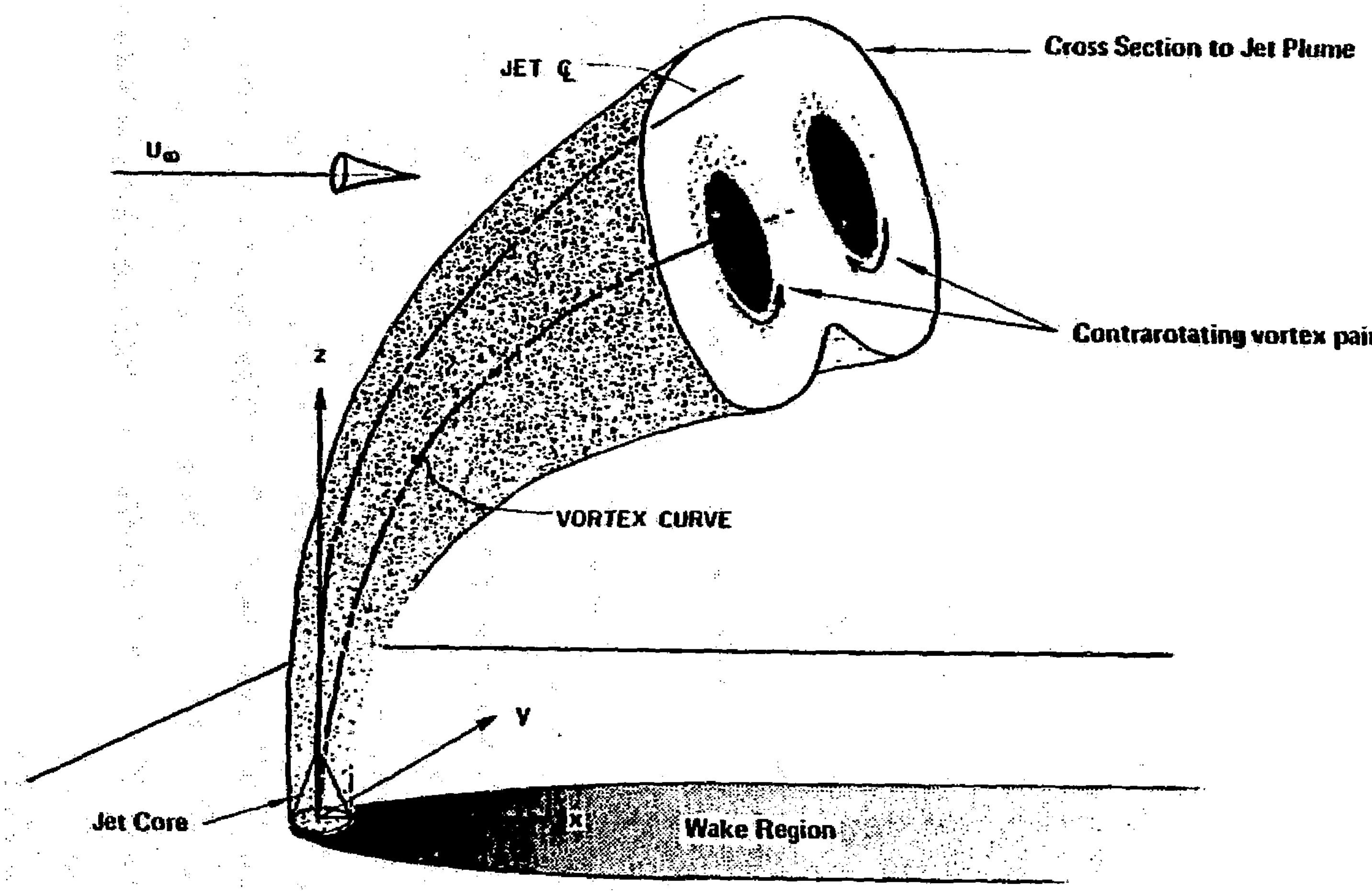

Figure 2. - Prominent Features of a Jet in a Crossflow.

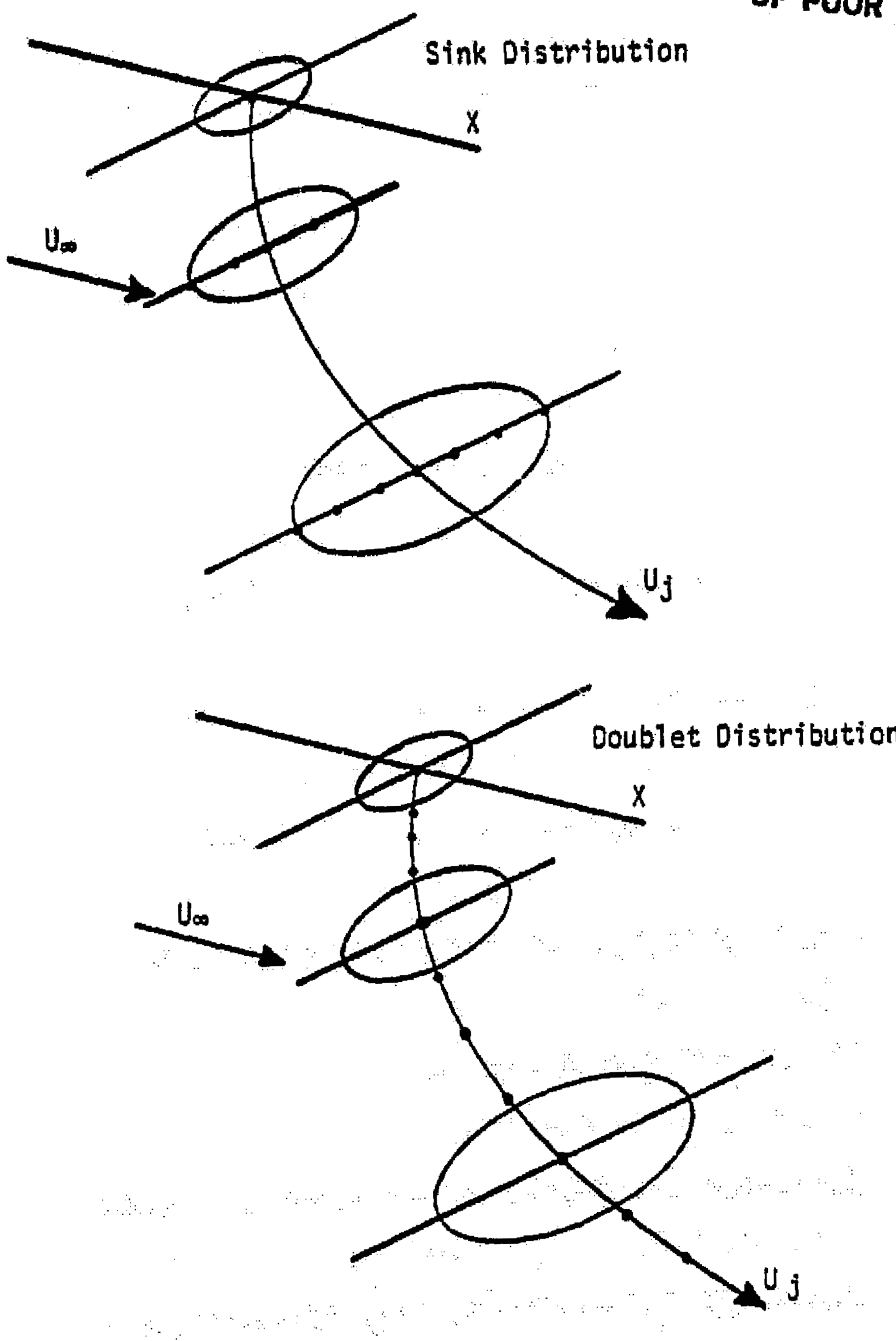

Figure 3. - Wooler Transition Jet Model.

three empirically determined coefficients. The values chosen result in a good correlation between experimentally and theoretically derived jet centerline locations. The doublets are distributed along the jet centerline and account for the jet blockage effect by creating a flow past an equivalent circular cylinder. This model is effective in predicting the induced perturbation velocities for aircraft configurations which do not include surface area behind a jet in crossflow. For configurations which do include surface area behind a jet in crossflow, Wooler's model, along with others, underestimates the magnitude of the negative pressures found in the wake region.

The Wooler model has been extended to include a wake correction by Walters and Yen.[19] This extension to the Wooler model consisted of a pair of short-lived, low-strength vortices incorporated into the wake area. The addition of these vortices resulted in an improvement in the prediction of the surface pressures on the flat plate. While this wake model improved the ability of the Wooler model to predict the pressure, force, and moments on the flat plate model, it still was not able to match the negative pressures found immediately aft of the jet core. This wake model, though applied to the Wooler model, could be adapted to other jet/aerodynamic-surface models.

An extension of the Wooler model has been made to model multiple jets in crossflow. This work, presented by Ziegler and Wooler,[20] gives methods for modeling both tandem and transverse jet/flat plate configurations. The model does not account for any viscous wake effects. In this method the case of transverse jets is modeled by assuming independent jets until the trajectories meet, then combining the jet plumes. For the tandem jet case, the crossflow speed on the aft

jet is decreased as a result of forward jet blockage, and the two jet plumes are combined as they meet.

The second model was presented by Dietz[7] in his masters thesis and later developed to its present form by Fearn.[8] This model assumes the two contrarotating vortices to be the dominant characteristics of the jet/flat plate configuration. A less dominant, yet still important characteristic, is the entrainment of freestream fluid into the jet plume. The model is implemented by placing a series of linear vortex filaments along the vortex paths, and a series of linear source segments along the jet centerline curve. The strength distribution for the vortex filaments is determined by inferring the vortex properties from the experimental data of reference 14.

Similar to the Wooler model, the model of Fearn is unable to predict the pressure distribution in the wake region. Fearn's model does, however, contain an empirical wake correction, which when used results in good correlation of model and experimental data for the pressure, force, and moment data for flat plate models. Fearn's model has been applied to the cases of a round jet/flat plate configuration with perpendicular jet injection and jet-to-crossflow velocity ratios from three to ten.

The third and final model discussed in this report was developed by Adler and Baron.[9] Their model is based on a control volume method. This model is a quasi-three-dimensional integral method used to solve the problem of an isothermal, incompressible, turbulent, round jet in a crossflow. The model is based on two integral momentum equations, one written for a direction parallel to the jet centerline and the other for a direction perpendicular to the centerline. The mathematical model is

numerically solved, producing a flow field within the jet plume. Results of this method, as reported in reference 9, show that it is capable of predicting the axial flow in close proximity to the jet plume, but does not adequately predict the velocity and pressure perturbations on configurations far from the jet plume. The Adler and Baron method is not restricted to a jet/flat plate configuration.

The choice of jet/flat plate model for this project is the method of Fearn. This Jet/Aerodynamic-Surface Interference (JASI) program is known as JASIB in its present form and is documented in reference 8.

Combined Methods

There is a need for a computer modeling method which combines a panel code with a jet/aerodynamic-surface model. At this time one method is in use which combines jet/flat plate models with panel codes. It is the one developed by Beatty and Kress. At the time of this writing there are a number of studies ongoing which are addressing this problem.[5] Unfortunately, reports on these studies are not available for description here.

The computer code developed by Beatty and Kress[21] is intended to model virtually all aspects of V/STOL flight. Their computer program uses the Hess potential flow code to model freestream effects on the aircraft. Supplementing the Hess code is a series of programs to model the propulsive effects on the aircraft. The propulsive effects section include: an inlet analysis section, three jet/flat plate sections, and a ground effects section. The three jet/flat plate sections are a modified Wooler[6] method, modified Weston[22] method, and the Thames and Weston[23] method for rectangular jets in crossflow. The modified Wooler method is essentially the same as that described earlier except for the

addition of a ground effects algorithm and a limitation that there be no more than two jets per jet system. The Weston[22] method is a version of the early work of Dietz and Fearn. The modified Weston model of Beatty and Kress is reported in reference 21 to be applicable to various injection angles, various jet-to-crossflow velocity ratios, and to multiple jets. The extension to handle multiple jets is similar to that presented by Ziegler and Wooler, as mentioned earlier. The ability to model various injection angles and velocity ratios is accomplished by extending the work presented by Dietz[7] in his masters thesis. The work of Thames and Weston[23] on a rectangular jet is limited to a jet with an aspect ratio of four. The jet is oriented with the major axis either parallel or perpendicular to the crossflow. The method used by Thames parallels that used by Dietz for the round jet case.

Results for the programs of Beatty and Kress, as given in reference 21, show that the modified Weston model gives surface pressure results which agree closely with the Wooler method. Both the modified Weston and Wooler methods give good agreement with experimental surface pressure data for regions exterior to the jet wake area; the need for a wake model for the jet wake region is stressed. Another area of concern presented in reference 21 is that of viscous and non-viscous interaction between the various elements of the entire program package, i.e., the interactions between the freestream flow section and the propulsive effects section.

Proposed Method

The objective of this proposed method is to determine the inviscid, potential flow field on and about a V/STOL aircraft in transitional

flight out of ground effect. The proposed method is based on the following assumptions:

1. A potential flow model, for the flow field induced by the jet plume of a known jet/aerodynamic-surface configuration exists. This model is referred to as the jet/base configuration model. The jet plume properties are assumed to be dependent on the following: the aerodynamic-surface configuration, jet orifice shape and velocity profile; jet injection angle, and the jet-to-crossflow velocity ratio.
2. The V/STOL aircraft configuration of interest is modeled with a potential flow panel code.
3. A local velocity ratio for the jet plume properties can be defined. For a jet/flat plate configuration, it is conventional to define the velocity ratio as either U_∞/U_j or U_j/U_∞. Where U_j is the jet exit velocity magnitude, and U_∞ is the crossflow velocity magnitude. For a local velocity ratio, the crossflow velocity is replaced with the local onset velocity, which can be a vector or a scalar quantity depending on the jet plume model. The local onset velocity is considered to be the velocity (or speed) at a point of interest in the jet plume (i.e., a singularity control point) due to all influences other than those of the jet plume under consideration.

The proposed method is implemented by following these steps:

1. Calculate the panel code singularity strength distribution. The onset flow to the panel control points is the sum of the freestream flow and all jet/base-configuration induced flows.
2. Use the results of step 1 to calculate the local velocity ratio for each point of interest in the jet plume(s).
3. Use the local velocity ratio for each point of interest in a jet plume to modify the jet plume properties.
4. Check for model convergence by comparing the jet plume property changes with a preset tolerance.
5. If the model has not converged then return to step 1 with the new jet plume properties. If the model has converged then the potential flow solution is complete.

The above method should, after convergence, produce a model which represents the jet/aerodynamic-surface configuration of interest better than if the method were stopped after step 1. The only criterion mentioned above for adjusting the jet plume properties is the local velocity ratio. There may be other criteria which are important to the jet plume properties.

Viscous flow modeling is not included in the proposed method. If a viscous flow model, i.e., a wake model, is required it could be added after the potential flow calculation section.

One should note that the above method describes the modeling of multiple jets in crossflow. The flow field of multiple jets in crossflow, all in close proximity to each other, has been observed, by Braden,[24] to be more complex than might be expected. Two better

procedures for handling multiple jets in crossflow might be: 1) to use a jet/base configuration which models multiple jets in crossflow; 2) construct a composite model similar to that of the Ziegler and Wooler method.[20]

Presented Model

Although the method proposed above to solve for flow about V/STOL aircraft is feasible at this time, it is not attempted for this report. As a test and demonstration of the method proposed, a first-order model, fabricated after the method described above, is developed, tested, and applied to two specific configurations. The first-order model is essentially the first step of the method proposed above. The model utilizes an empirical jet plume model from a jet/flat plate configuration, for the jet influences on the lifting surface configuration. The model has no interaction between multiple jets in crossflow, although it will accommodate multiple jets in crossflow on the lifting surface configuration. Also, due to the non-iterative design of the model, the lifting surface has no influence on the jet properties. The first-order model is limited by the jet/flat plate model to the case of subsonic uniform round jets injected perpendicularly into a subsonic uniform crossflow. with jet-to-crossflow velocity ratios from three to ten.

The computer model presented here is assembled by combining a modified version of the Jet/Aerodynamic Surface Interference program (JASIB) of Fearn,[8] as a set of subroutines, with a low-order panel code for three-dimensional lifting surfaces in subsonic inviscid flow (WBABL).[10] The model presented is verified by modeling a flat plate[25] with a round jet in a crossflow. Two other configurations modeled are a

symmetrical airfoil[26] and a streamlined body of revolution.[27] The results of each configuration tested are compared with experimental data in the form of surface pressure coefficients and integrated body forces and moments, where they are available.

SECTION III
COMBINING TWO COMPUTER CODES

The two computer modeling codes to be combined are WBABL, a low-order panel code, and JASIB76, a jet/flat plate modeling code. The JASIB76 code is a direct extension of the JASIB code, developed by Fearn.[8] The JASIB code models the flow over a flat plate with a round jet injected perpendicularly into the freestream flow. The JASIB76 code is primarily designed to function as a group of subroutines on a CDC-7600 computer, and to be independent of any surface configuration. The WBABL panel code is a low-order panel code for solving the flow about a wing/body combination. The WBABL code also has a boundary layer iteration section which is not utilized in the combined computer code. Both computer codes are written in FORTRAN IV.

WBABL Computer Code

The general structure of WBABL is shown in Figure 4, the WBABL flow chart. The actual program is made up of a series of overlays, to meet the memory requirements of the CDC-7600 computer system. The overlay structure is shown in Figure 5. The executive program, WBABL, shown as Overlay (0,0), controls the overall panel code by calling in turn the potential flow overlay, WBOLAY, and the boundary layer overlay, INTEGRAL. The calculation sequence for the WBABL panel code is as follows:

Loft geometry. All input parameters for the lifting and non-lifting surfaces are read in the overlay WBPAN. The planar panels are

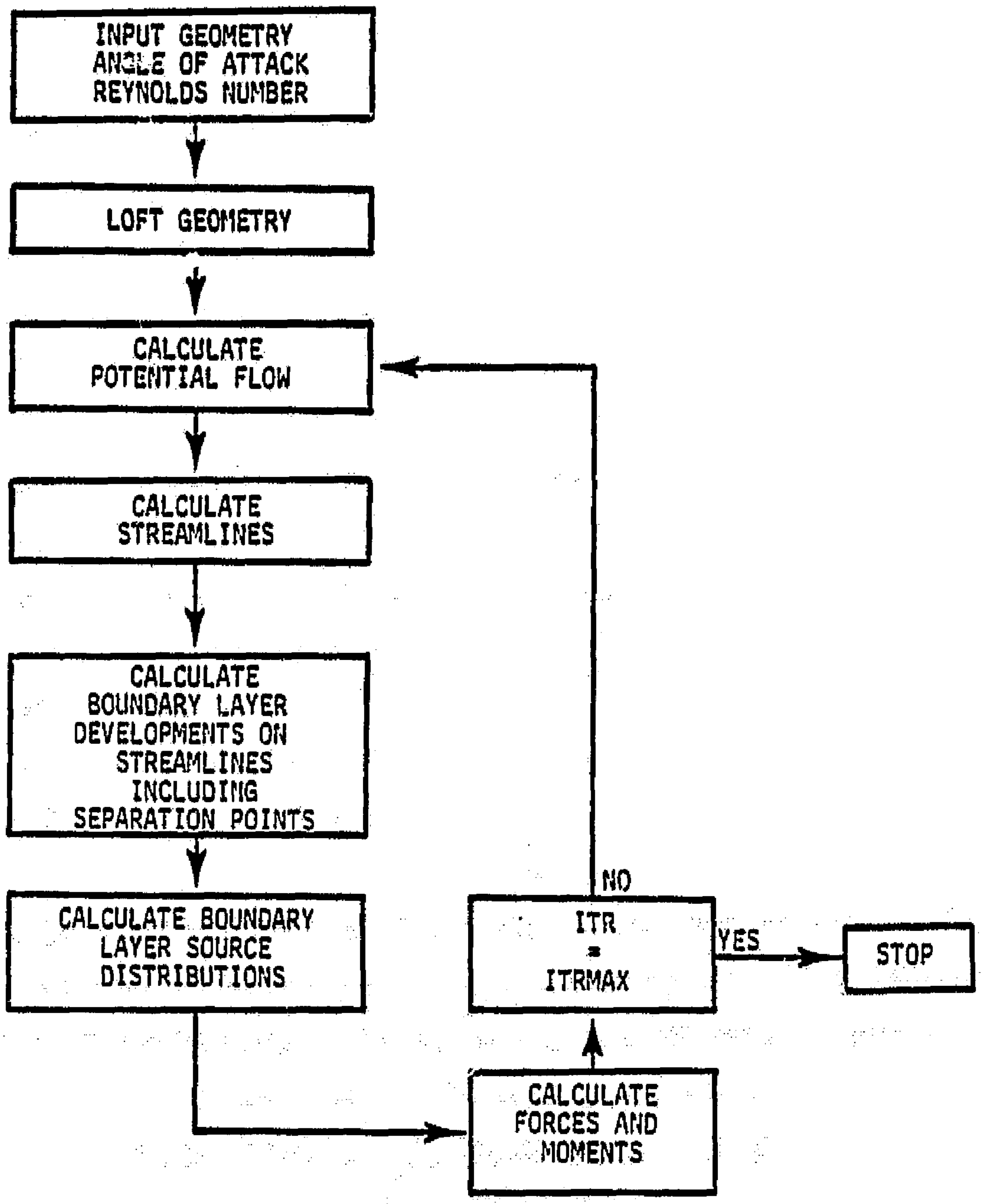

Figure 4. - WBABL Program Flow Chart.

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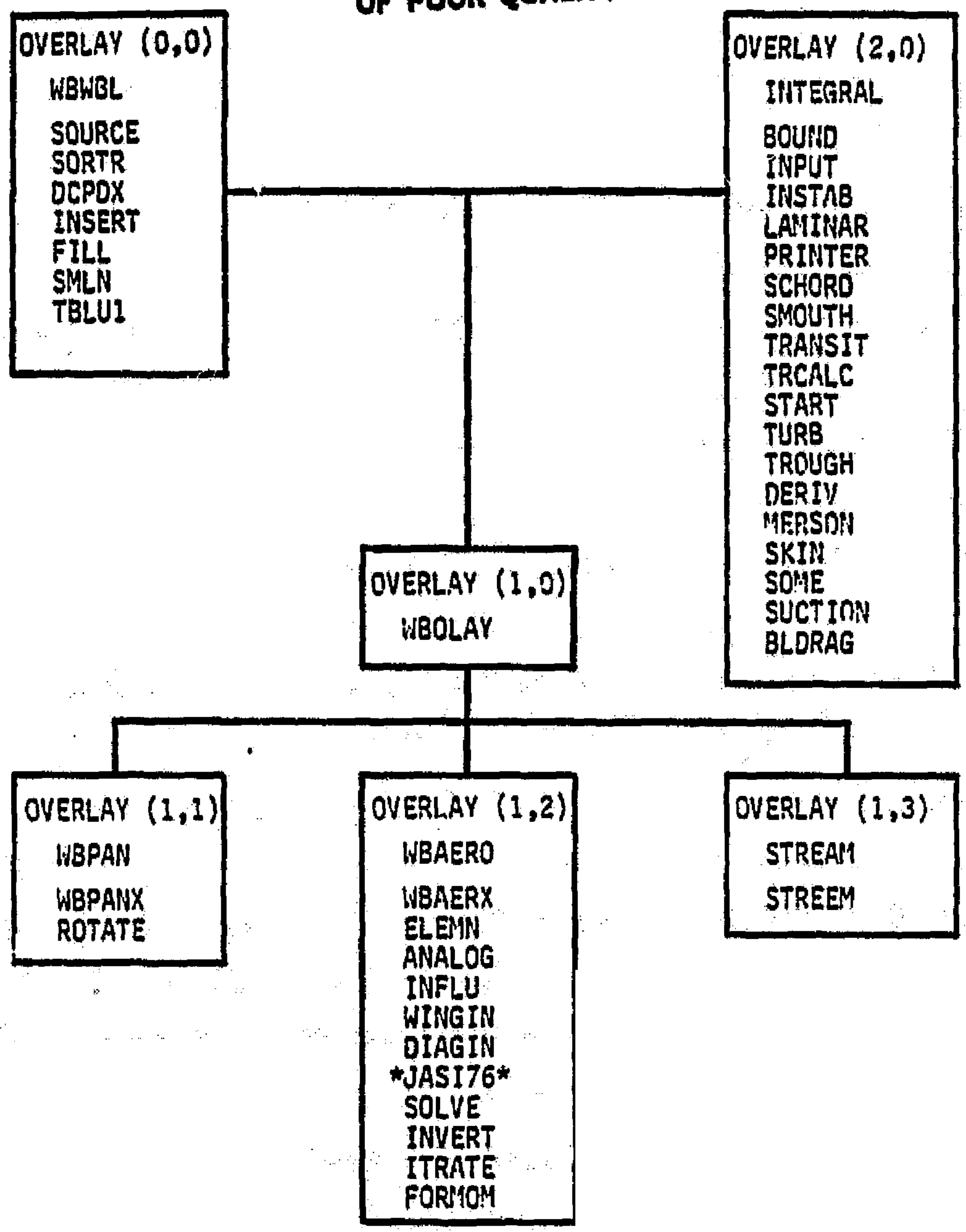

Figure 5. - Overlay Structure of the WBABL Program.

lofted and the lifting surface vortex network is laid out. The X, Y, Z coordinates of the four panel corner points, for all surface and vortex panels being considered, are calculated and written to an auxiliary file and the output file.

Calculate potential flow. Within the WBAERO overlay all potential flow calculations are made. Due to the numerous computations made in this overlay, it is the largest overlay of the entire panel code structure. WBAERO executes as follows: The corner points computed in WBPAN are read from an auxiliary file. Subroutine ELEMEN is then called for each panel. This subroutine calculates the control point locations and the transformation matrix, and then transforms the corner points from the reference coordinate system to the panel coordinate system. The panel control and corner points are then transformed to an analog body by subroutine ANALOG. This is required by Göthert's compressibility rule and is done whenever the freestream Mach number is greater than one-tenth. Subroutines INFLU and WINGIN calculate the velocity influence coefficients induced by unit source singularities and unit vortex singularities, respectively. These influence coefficients are combined to form the aerodynamic influence coefficient matrix. The boundary conditions, i.e., zero normal flow at each panel control point, are calculated for each angle of attack and yaw. With the above information the system of algebraic equations relating the singularity strengths and the boundary conditions is solved for the source and vortex strengths in subroutine SOLVE. With the singularity strengths known, the velocities at the control points are determined. With the velocities known, the surface pressures are determined. The forces and moments on the body are found in subroutine FORMOM. A more detailed

description of the above procedure is given in the theory section of reference 11.

Streamline calculation. Overlay STREAM calculates the trajectory of up to twenty-five body streamlines. The starting location of the streamlines can be any control point. The streamline is traced fore and aft to the body limits.

Boundary layer calculation. Overlay INTEGRAL contains the boundary layer calculation subroutines, which determine laminar and turbulent boundary layer development along the streamlines specified above. A detailed description of the boundary layer subroutines is given in reference 10. They are not utilized for this study and are not discussed here.

Modification of the WBABL panel code for inclusion of a jet-in-crossflow module is necessary if the effects of jets in crossflow are to be evaluated. The ideal solution to the problem of how to integrate the jet-in-crossflow module into WBABL would be to create a new overlay for the jet effects. This is not possible, however, because of the overlay hierarchy and the existing structure of WBABL. The input to the jet code requires that it be addressed after the control points are defined, e.g., within WBAERO. The output from the jet code and the jet perturbation velocities, must be available to WBAERO for inclusion in the control point boundary condition calculation. These requirements dictate that a jet overlay be addressed from within the WBAERO overlay, but a second level overlay, (i.e., WBAERO) can not call other overlays.

The fact that the jet-in-crossflow module can not be an overlay necessitates that it become a group of subroutines within the WBAERO overlay. This requirement brings about new complications, in the form

of available memory. WBAERO is the largest overlay of the entire WBABL package, thus occupying the maximum memory. The maximum number of panels (control points) that a configuration can have is limited by available memory, which is controlled by the size of the programs and subroutines within the memory. Thus, in order to have a jet-in-crossflow module within the panel code, the panel code must sacrifice its most valuable asset; its ability to model large complex configurations and still maintain accuracy with a fine panel network.

JASIB76 Computer Code

The JASIB76 program is a direct descendent of the JASIB program developed by Fearn.[8] The JASIB program calculates the pressure distribution induced on an infinite flat plate at zero angle of attack, due to the influence of a single round jet in a crossflow. The flat plate is modeled by the method of images, and the pressure coefficients at the control points on the plate are found by the application of the incompressible Bernoulli's equation. The JASIB76 program is a group of subroutines, controlled by an executive subroutine, which computes the perturbation velocities, at a specified point, due to the jet plume properties of a jet/flat plate model. The properties of the jet/flat plate model used in JASIB76 are those of a round, uniform, subsonic jet injected perpendicularly into a uniform subsonic crossflow from a flat plate. The jet-to-crossflow velocity ratio must fall between three and ten. A flow chart outlining the structure of the JASIB76 module is shown in Figure 6.

The JASIB76 executive program oversees the computation procedure by systematically calling each of the subroutine groups. Contained within the executive program, in the form of comment cards, is a brief history

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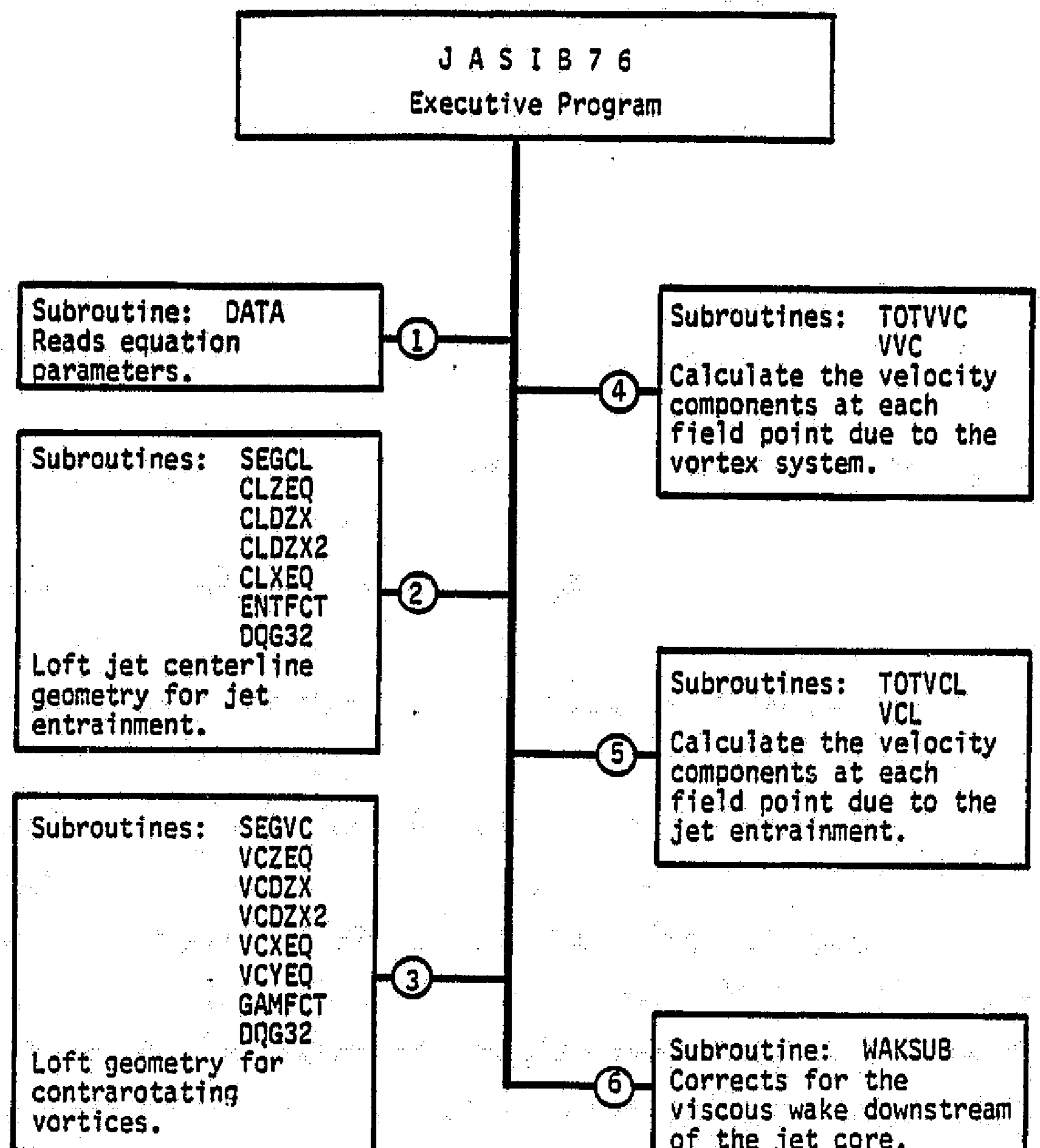


Figure 6. - JASIB76 Flow Chart.

of the JASI programs and a description of each subroutine within the module. The executive program in the module JASIB76 receives the FORTRAN CALL statement from the outside program, in this case WBABL. The CALL statement to JASIB76 contains the arrays specifying the field points of interest and the jet perturbation velocity arrays associated with the field points. Both the field points and velocity components are in the panel code reference coordinate system. Variables passed to JASIB76, from the panel code, through COMMON statements are the following: the location of the jet center; jet diameter, D; jet to crossflow velocity ratio, R; jet injection angle, δ; angle of attack, α; yaw angle, β; and the jet roll angle, γ. The dimensional units given in the list above are all in the panel code reference coordinate system. The subroutine sections called by the executive program are described below in the order of their calling.

DATA. This subroutine reads from the input file the options and parameters for the jet/flat plate model. The values in the parameter sets are dependent on the following jet properties: velocity ratio, R; injection angle, δ; jet exit shape and profile.

SEGCL. This section approximates the jet plume centerline geometry. The jet centerline is broken into linear, constant strength source segments to model the jet entrainment. The SEGCL subroutine calls six other subroutines in order to divide the jet centerline and determine the source strength on each segment.

SEGVC. The SEGVC section approximates the geometry for the vortex paths. As in the SEGCL section the vortex paths are segmented and constant strength vortices are placed on each segment. Only the starboard vortex path is approximated; the geometry of the vortex paths

is symmetrical about the x-z plane in the jet coordinate system. The vorticity on the port vortex segments is equal in strength and opposite in sign to that of the starboard segments.

TOTVVC. This section calculates the velocity induced at the field points by the contrarotating vortex system. Contained in TOTVVC is the calculation of the transformation matrix for relating the jet coordinate system, as shown in Figure 2, to the panel code reference coordinate system, as shown in Figure 1. The transformation matrix is used to transform the field points to the jet coordinate system and the velocity components from the jet coordinate system into the panel code reference coordinate system. The subroutine VVC, which is called by TOTVVC, is the routine which actually calculates the perturbation velocities for each field point.

TOTVCL. The TOTVCL subroutine, which uses subroutine VCL, is synonymous in function to TOTVVC, in that it calculates the perturbation velocities at the field points due to the jet plume entrainment. Subroutine VCL is called by TOTVCL. VCL calculates the perturbation velocity for each field point.

WAKSUB. Subroutine WAKSUB is used to model the wake region downstream of the jet in a crossflow. At the time of this writing the wake subroutine is inactive in the JASIB76 program module. The reason for the lack of a wake subroutine is that the only wake model available, at the time the program was coded, was an empirical correction subroutine which works directly with the surface pressures; only the jet perturbation velocities are available in the jet module. At present wake modeling is handled by a post-processor unit, which modifies the

pressure distribution downstream of the jet after the main program has finished execution.

Output from the JASIB76 program is provided through three channels: the CALL statement addressing JASIB76, COMMON blocks, and the panel code output file. The jet perturbation velocity components for each field point are provided through the CALL statement; the perturbation velocities are added to the values provided by the CALL statement at the initiation of JASIB76. The isentropic jet thrust components, in the panel code reference coordinate system, are output through the COMMON blocks which link the panel code to the jet module. The output, written to the output file, is dependent on the diagnostic and output options specified in the jet input parameters. Diagnostic output from JASIB76 consists of the following: all input parameters and control point locations; geometry for the jet centerline and the starboard vortex; vortex induced velocities at a field point for all vortex segments; total vortex induced velocity for all field points; entrainment induced velocities at a field point for all centerline segments; total entrainment induced velocity for all field points; and the jet thrust components.

Recall from the previous description of WBABL that the overlay WBAERO occupies the largest quantity of core memory, and that the JASIB76 code must be placed in this overlay. For this reason the core memory requirements of JASIB76 are reduced. The primary method of reducing the core memory requirements of a program executing on the CDC-7600 computer is to place as many variables as possible in the Large Central Memory (LCM) region of the computer. All variables in labeled COMMON arrays within JASIB76 are placed in LCM. As a result of placing

all possible arrays in LCM, the JASIB76 program requires only three variable arrays to be in the core memory. These are the perturbation velocity components. Each of the velocity arrays is dimensioned to the number of control points. The only other arrays in core memory of any significant size, are the field point locations, and they are required to be in core memory by the panel code, WBABL.

The Combined Computer Code, WBWJAS

The combined computer code, known by the acronym WBWJAS, is formed by adding the JASIB76 module to the WBABL panel code as a set of subroutines in the WBAERO overlay. A flow chart of the WBWJAS execution is shown in Figure 7. The flow chart shows that the structure and flow of the WBWJAS program is identical to WBABL, except for the addition of jet effects before the potential flow calculation. If the WBWJAS program is executed without jets in crossflow, the execution and output would be identical to that of the WBABL program.

The execution of WBWJAS with a jet in crossflow will differ from WBABL as follows. After lofting the geometry for the body and wing panel networks, the program reads to determine if there will be any jets in crossflow and if so how many. The panel code next determines the velocity field perturbations due to unit singularity strengths on the source and vortex panels. This is the same as WBABL. When all geometry is known, WBABL calls the JASIB76 module, passing it the field points and jet perturbation velocities for each field point. When execution returns from JASIB76, the value of the jet perturbation velocities is the input value plus the value determined for the jet that was just addressed. After all jets in crossflow have been addressed, the panel code treats the jet perturbation velocities as if they are a part of the

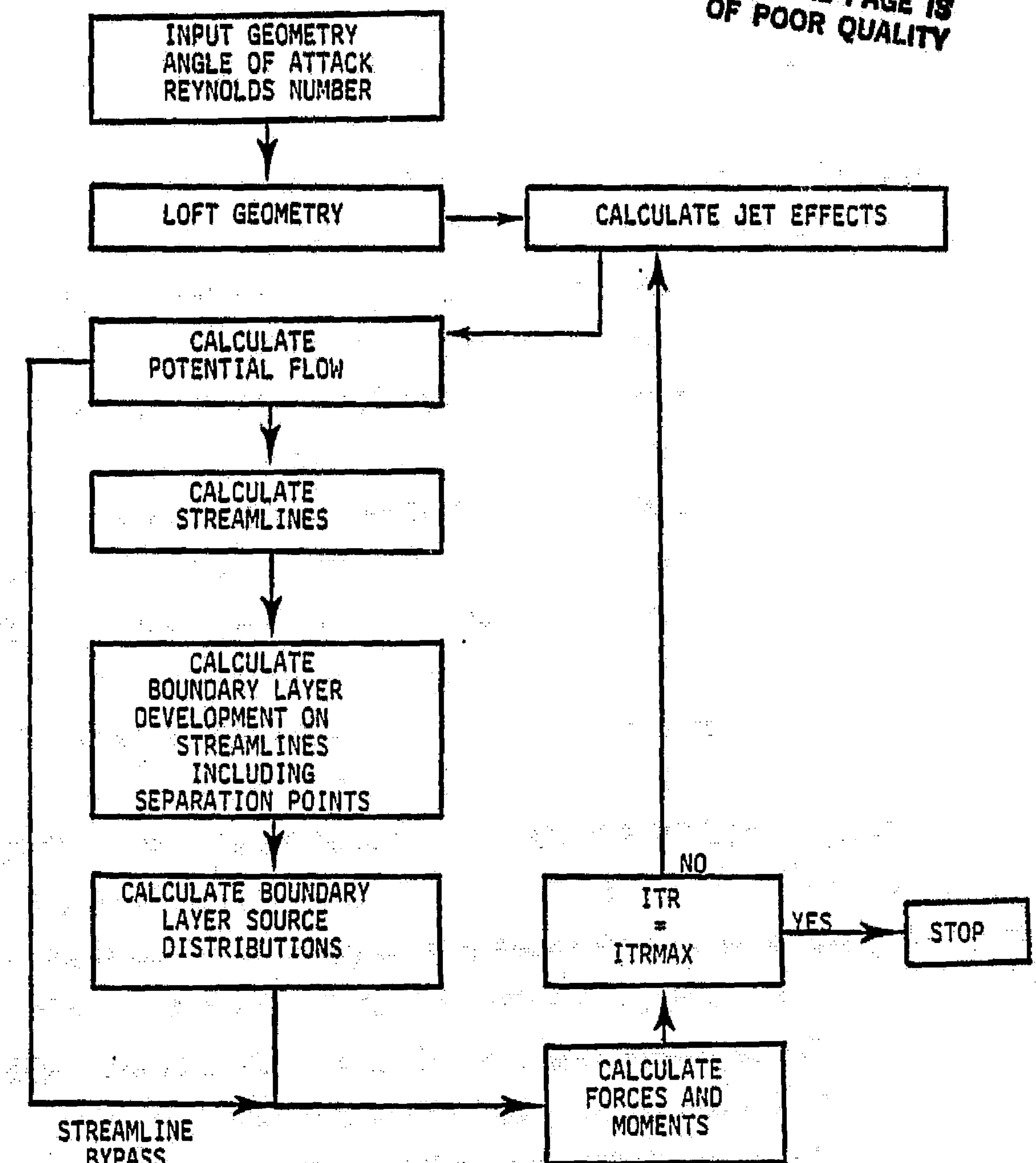


Figure 7. - WBWJAS Program Flow Chart.

freestream flow. The right side of the matrix equation, the boundary conditions, is computed using the jet-in-crossflow perturbation velocities as components of the freestream flow. The matrix equation is solved, as it would be in the non-jet in crossflow case, for the singularity strengths. With the singularity strengths known, the velocity at each control point is the sum of the freestream velocity and all perturbation velocities. The pressure coefficients at each control point are then found using Bernoulli's equation. This completes the potential flow calculation for WBWJAS.

The streamline tracing and boundary layer calculation sections follow the potential flow calculations. These sections do not have to be exercised when executing the panel code and for this thesis they are not exercised. The final computation in the panel code is the numerical integration of the pressure distribution in order to determine the forces and moments. The decision block in the flow chart (Figure 7) following the force and moment calculation, ITR=ITRMAX, refers to the number of angle of attack cases being investigated. If only one case is used the program would stop execution after the first complete run.

The WBWJAS program is not without limitations. The program contains most of the limitations of the WBABL and JASIB76 programs plus others. The reader is reminded of three main limitations to JASIB76: it models a round uniform, subsonic jet injected perpendicularly into a uniform subsonic crossflow; the jet-to-crossflow velocity range is valid from three to ten; and the model properties at this time are based on a jet/flat plate configuration. The limits of WBABL are as follows: it does not model the interference effects of jets in crossflow; it is

limited to 1500 total control points on one side of the X-Z symmetry plane; and it is limited to subsonic attached flow only.

The limitations of the combined program, WBWJAS, which are not mentioned above are included now. The code is restricted to approximately 660 total control points on one side of the X-Z symmetry plane, due to memory restrictions. The influence of the lifting surfaces on the jet properties are not accounted for. There are no interactions between multiple jets in crossflow, and the wake region downstream of the jet core is not modeled.

The input/output structure of WBWJAS is simply a combination of the WBABL and JASIB76 codes, with all options of each code still available.

SECTION IV
CONFIGURATION TESTING

Three basic configurations are tested using the WBWJAS panel code with jet-in-crossflow effects. The three configurations are a finite flat plate, a body of revolution, and a symmetrical airfoil section. The panel code configurations are paneled to match as closely as possible the configurations which were tested in low speed wind tunnels. The first configuration tested, the flat plate, is used as a tool to verify the WBWJAS program execution. The body of revolution and the symmetrical airfoil are both examples of easily modeled generic configurations, for which wind tunnel pressure data is available.

Flat Plates

Three flat plate configurations are utilized in the development of the WBWJAS program. The first is used only for program development work to verify any modifications. It is a thin, rectangular grid, eighty-four control point flat plate with no thickness. The second flat plate is also used for developmental testing and is not presented as a data source. This plate is rectangular with a finite thickness. The upper surface is a radial grid with the jet located at the center. The lower surface is a rectangular grid; its edges are level with the upper surface. The final flat plate, which is used for actual testing purposes, is a thin, rectangular grid plate. The semi-span dimension is 100 units with the chord length variable. The final chord length is 165 units and the panels are five units square. These dimensions yield a

final configuration of 660 panels. The jet in crossflow is located at (75,0,0) and has a variable diameter. The final jet diameter is ten units. As tested the flat plate dimensions in jet diameters are length 16.5 D, width 20 D; the jet is located on the centerline 7.5 D from the leading edge. The reference coordinate system is located at the leading edge along the plane of symmetry. The reference angles α, β, and γ are all zero, indicating the jet coordinate system is parallel to the reference coordinate system.

The flat plate configuration is used to determine the maximum number of panels a configuration can have, and to determine the acceptable range of panel densities, which give satisfactory results, in the near jet region. The maximum number of panels is found by varying the plate chord. The acceptable range of panel densities can be found by varying the jet diameter.

The wake region downstream of the jet core is modeled by an empirical wake correction scheme as described in reference 8. The wake correction is in a post-processor unit to the panel code and modifies only the surface pressure distribution. The wake correction uses the empirical pressure distribution, along the downstream ray from the jet orifice, to estimate a correction factor which is applied to the pressure distribution within the wake region.

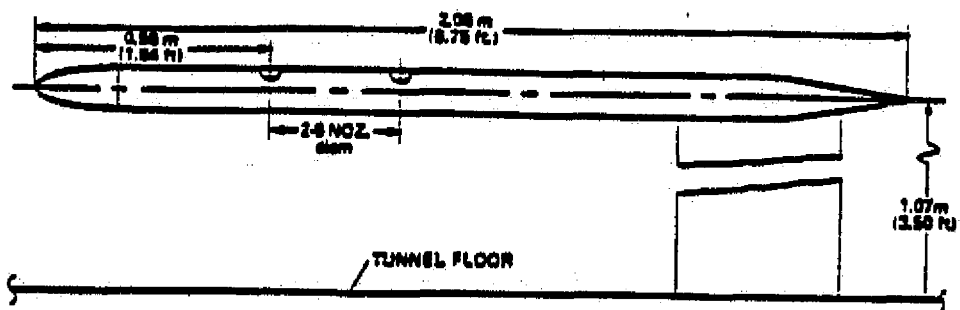
Body of Revolution

Many experimental investigations of jet-in-crossflow flow properties have placed attention on flat plate configurations, or jet-in-lifting surface configurations. These configurations have little if any curvature of the lifting surface near the jet in crossflow. Few investigations have been made of a jet/aerodynamic-surface configuration

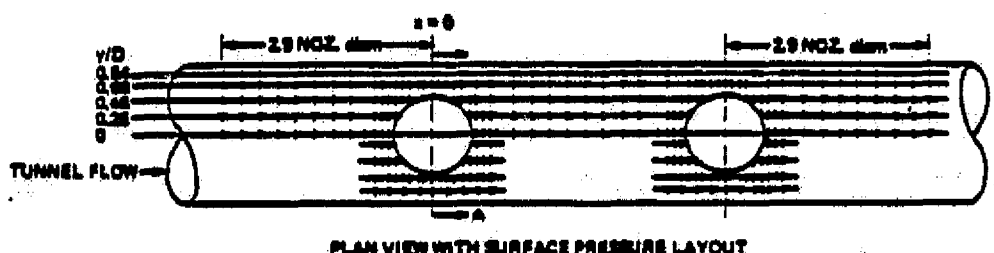
with a high degree of surface curvature near a jet in a crossflow (e.g., a jet/fuselage configuration). A single engine V/STOL aircraft will probably have lift jets located in the fuselage, for the simple reason that locating them elsewhere would require complex ducting, adding extra weight and expense. The simple generic model for a fuselage is a body of revolution. A recent wind tunnel investigation,[27] at NASA Ames Research Center, studied the surface pressure distribution on a body of revolution with various jet configurations. The body-of-revolution configuration studied at NASA is modeled here with the WBWJAS computer code, for the case of a single jet in a crossflow with perpendicular jet injection.

The body-of-revolution model tested by NASA is shown in Figure 8, which is reprinted from the test report.[27] The model is four inches in diameter and eighty-one inches in length. The jet diameter is 1.94 inches. The model has a wooden, streamlined nose, and is strut supported at the rear. The jet center for the single jet case is located twenty-two inches from the nose. Two jet nozzle exits were used. The first was flush with the surface of the body, which is referred to as a contoured exit. The second, a flat top exit, was level with the top of the model.

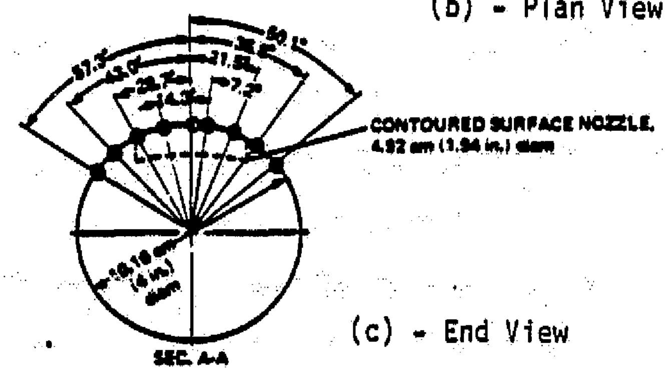
The computer configuration of the body of revolution is paneled to approximate the control point locations to the pressure ports on the wind tunnel model. The computer configuration is divided into six axial sections known as patches. The patches are paneled using the body-of-revolution geometry option in WBWJAS. The patch structure is shown in Figure 9, along with an end view showing the panel structure in the jet region. The nose, forebody, aftbody, and tail patches are



(a) - Dimensioned Sketch

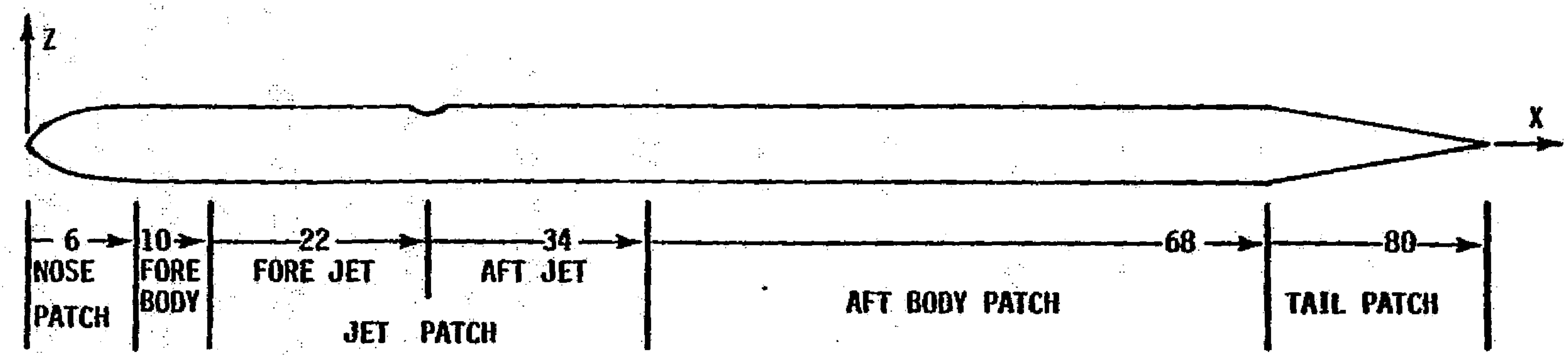


(b) - Plan View

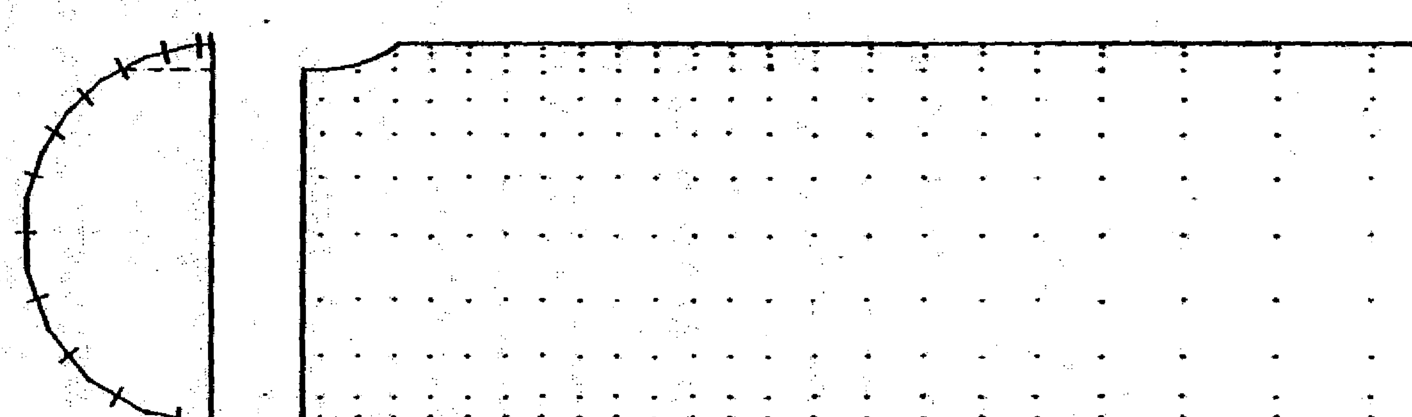


(c) - End View

Figure 8. - Body of Revolution Model (reference 27).



(a) Side view, patch detail.



(b) Aft jet detail, dots are control points, ½ scale.

Figure 9. - Body of Revolution Model, Computer Lofting.

coarsely paneled, such that they maintain the body shape with a relatively small number of panels. The jet patch is simulated with a fine panel grid, approximating the pressure port locations on the test model. The jet patch contains 540 panels and all other patches combined have 120 panels. The reference coordinate system origin for the body-of-revolution model is located at the nose of the model, as shown in Figure 9. All length units are relative length units based on a body diameter of four units. The jet in crossflow is located at (22,0,2.0) for the flat top exit, and (22,0,1.732) or (22,0,1.5) for the contoured exit. The jet is two units in diameter. The orientation angles α, β, and γ are all zero.

A wake correction is not applied to WBWJAS for the body-of-revolution models. As will be seen in the next section, the data shows that a wake correction is not needed for this configuration.

Symmetrical Wing Section

Throughout the early sections of this thesis it is stressed that WBWJAS does not model the influence of lifting surfaces on the jet-in-crossflow properties. To investigate the lifting-surface influences, a symmetrical wing section is modeled. The symmetrical wing section modeled is similar to a jet/wing configuration that was tested by Mikolowsky,[26] in the Georgia Institute of Technology nine-foot low-speed wind tunnel. The data from the WBWJAS model are compared with data from the wind tunnel model.

The wind tunnel model spanned the entire test section with a NACA 0021 airfoil section whose chord was 15.37 inches. Two jet configurations were tested and are now described. The first jet configuration had a diameter of 1.5 inches, with the jet centerline exit

location at either 25, 45, or 65 percent chord. The second had a jet exit diameter of 3.0 inches exiting at 45 percent chord. The jet-to-crossflow velocity ratio was varied in the range from two to twelve. The tests were performed at three wing angles of attack: 0°, 6°, and 9°.

The computer configuration paneled for WBWJAS is that of a finite semi-span wing. It has a NACA 0021 airfoil section with a chord length of 15 units, and an aspect ratio of twenty. The jet diameters used are 1.5 units and 3.0 units, and are placed in the wing at identical locations to those on the wind tunnel model. The configuration is tested at jet-to-crossflow velocity ratios of four and eight, and angles of attack of 0° and 6°.

The wing is not paneled such that the control points coincide with the pressure port locations. The wing model is divided into three patches. They are a near-field patch, a mid-field patch, and a far-field patch. The near-field patch extends from the symmetry plane, on which the jet is located, to a point 4.5 units in the spanwise direction. The near-field patch contains ten spanwise sections, each containing forty-six panels (thirty on the lower surface and sixteen on the upper surface). The mid-field patch, extending from 4.5 units to 15.0 units in the spanwise direction, contains four spanwise sections. Each spanwise section contains sixteen panels on the lower and upper surfaces, for a total of thirty-two per section. The far-field patch extends from 15.0 units to 150.0 units in the spanwise direction, and contains a total of forty-eight panels in six spanwise sections.

The jets are always located along the plane of symmetry and exiting the lower surface of the wing perpendicular to the freestream flow. In

the wind tunnel model the jets were perpendicular to the chord line, giving non-perpendicular jet injection angles. For the computer model the injection angle is always perpendicular to the crossflow, regardless of the wing angle of attack. The jet is located on the wing lower surface. The reference angles are the following: α, equal to wing angle of attack; β, always zero; γ, always one hundred eighty degrees, so the jet exits from the wing lower surface.

A wake correction is made to the computer generated data. This wake correction is identical to the one used on the flat plate configuration. This wake correction is applied only to the surface pressure data, and not to the force and moment data. As a post processor section, the wake correction scheme could not be supplied with the necessary data to correct the force and moment data.

SECTION V
RESULTS AND CONCLUSIONS

Flat Plates

Flat plate models are used primarily to debug the program and validate the numerical methods. The third flat plate, mentioned earlier as having a variable plate chord and variable jet diameter, is used to find the maximum number of control points permissible. The maximum number of control points that can be used in the WBWJAS program is dependent on the amount of core memory available, and is independent of the configuration being tested. The maximum number of control points is found by varying the flat plate chord length while maintaining a constant panel size. For the CDC-7600 computer system at Ames Research Center the maximum number of control points is six hundred sixty.

The jet diameter is varied on the flat plate, while maintaining a constant panel size, to determine an acceptable range and value, for the ratio of the jet diameter to the control point spacing, $R_{D/Sp}$. The ratio $R_{D/Sp}$ is synonymous to the panel density, and is important only within the near-jet region, i.e., within approximately four jet diameters of the jet orifice. The criterion for finding the acceptable range of the ratio $R_{D/Sp}$ is the agreement of surface pressure contour co-plots. This criterion can be interpreted as finding the minimum number of data points per unit area necessary for the particular contour plot program being used. This is not the intent of the criterion. The intent of the criterion is to find the acceptable range for $R_{D/Sp}$

required to yield an acceptable pressure distribution on the surface of interest. A maximum ratio can be found by testing for the effects of roundoff error in either the output data or resulting contour plots. Good agreement between the computer pressure contours and the experimental pressure contours for a jet/flat plate model are found for $1.0 < R_{D/Sp} < 5.0$. At values of $R_{D/Sp}$ greater than 5.5 the effects of roundoff error become evident, and below 1.0 the data is too sparse for the contour plotting program to produce smooth contour lines. Agreement of pressure contours is found to begin at values of $R_{D/Sp}$ = 2.0 and continue to 4.0 . Thus the value of $R_{D/Sp}$ used for the flat plate models is $R_{D/Sp} = 2.0$.

Surface Pressure Data

A comparison of pressure coefficient contour lines is made, for three different sets of data, in Figure 10. The three data sources are all for a uniform round jet issuing perpendicularly into a uniform crossflow from a flat plate. The three data sources are experimental data from reference 25, WBWJAS, and JASIB[8] which models the flat plate as an infinite plate by the method of images. The figure shows satisfactory agreement between the three data sources for all contour lines shown.

Force and Moment Data

The interference lift and pitching moment effects of the jet in a crossflow on the flat plate are also documented. The interference lift is non-dimensionalized by the isentropic jet thrust and is defined

$$\frac{\Delta L}{T_j} = \frac{L_{jet\ on} - L_{jet\ off} - T_j}{T_j} .$$

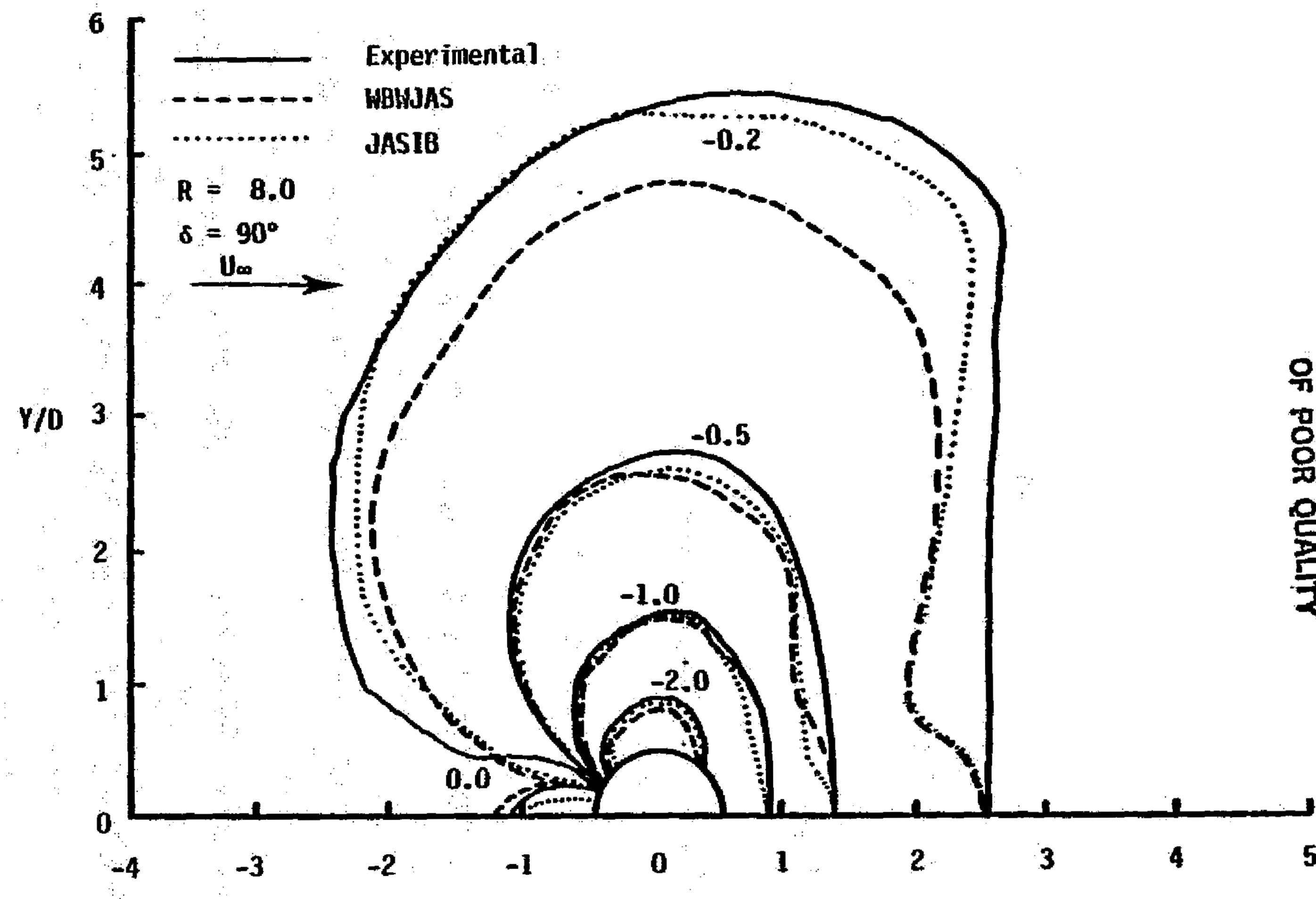


Figure 10. - Flat Plate, Surface Pressure Contours.

The interference pitching moment about the jet center is non-dimensionalized by the product of the isentropic jet thrust and the jet diameter, and is defined

$$\frac{\Delta M_j}{T_j d} = \frac{M_{j\ \text{jet on}} - M_{j\ \text{jet off}}}{T_j d} \quad .$$

The lift and jet thrust for the flat plate are defined to be positive in the negative "Z" direction of the panel code coordinate system. The pitching moment is defined positive in the negative "Y" direction for a right hand coordinate system.

The interference lift and pitching moment on the flat plate are given in Table 1. The data from the WBWJAS program is presented with and without a wake correction. The data from reference 8 for the JASIB program, with and without a wake correction, is provided for comparison with WBWJAS data. It should be noted that the forces and moments provided by JASIB and the experimental data are produced by numerically integrating the surface pressure distribution over a reference circle. This reference circle is centered at the jet center and has a diameter of eleven jet diameters. Force and moment data from WBWJAS are determined by using an area which approximates the reference circle for numerical integration of the surface pressures. The differences in the force and moment data reflect the differences in the surface pressure contour plot, Figure 10, for this flat plate configuration.

TABLE 1. - INTERFERENCE FORCES AND MOMENTS

CASE	MODEL		EXPERIMENTAL	
	$\frac{\Delta L}{T_j}$	$\frac{\Delta M_j}{T_j d}$	$\frac{\Delta L}{T_j}$	$\frac{\Delta M_j}{T_j d}$
FLAT PLATE[a]				
WBWJAS Data, no wake	-0.20	-0.091	-0.25	0.013
JASIB Data, no wake	-0.20	-0.075	-0.25	0.013
WBWJAS Data, wake correction	-0.23	0.012	-0.25	0.013
JASIB Data, wake correction	-0.25	0.018	-0.25	0.013
BODY OF REVOLUTION[b]				
Flat Top Exit, R=8, ZJCT=2.00	-0.04	0.12		
Contoured Exit, R=8, ZJCT=1.732	-0.10	0.09		
Contoured Exit, R=8, ZJCT=1.50	-0.16	0.06		
Contoured Exit, R=4.7, ZJCT=1.732	-0.26	0.17		

[a]Experimental data from Reference 25.

[b]No experimental force and moment data available.

Body of Revolution

The body-of-revolution model is intended to investigate the usefulness of the WBWJAS program for modeling bodies with high degrees of curvature near the jet in a crossflow. The model utilized, as described earlier, has a body-to-jet diameter ratio of two. The body-of-revolution data is presented without a wake correction. Data is presented for four body-of-revolution configurations. The first three configurations have a common value of the jet-to-crossflow velocity ratio of eight; the jet center location "Z" value is varied in the three configurations. The fourth configuration is with the velocity ratio equal to 4.7 .

Surface Pressure Data

The surface pressure data, provided by WBWJAS, are compared with the results of the NASA experiment.[27] The data is presented as interference pressure coefficients. These are defined as the pressure coefficient with the jet on, less the pressure coefficient with the jet off. Both values are measured at equivalent test conditions. The data is presented as plots of axial variations in interference pressure coefficients, ΔCp. The axial plots are presented for constant Y/D cuts of 0.0, 0.24, 0.47, and 0.84.

Figure 11 presents four surface pressure plots for a jet center "Z" value (ZJCT) of 2.0 . This configuration is representative of a flat top jet exit. Experimental data for a similar configuration is also shown in these plots. The data from WBWJAS, plotted as a solid line, agrees well with the experimental data.

Figures 12 and 13 present data for ZJCT values of 1.732 and 1.50, respectively. These values of ZJCT are intended to model the contoured

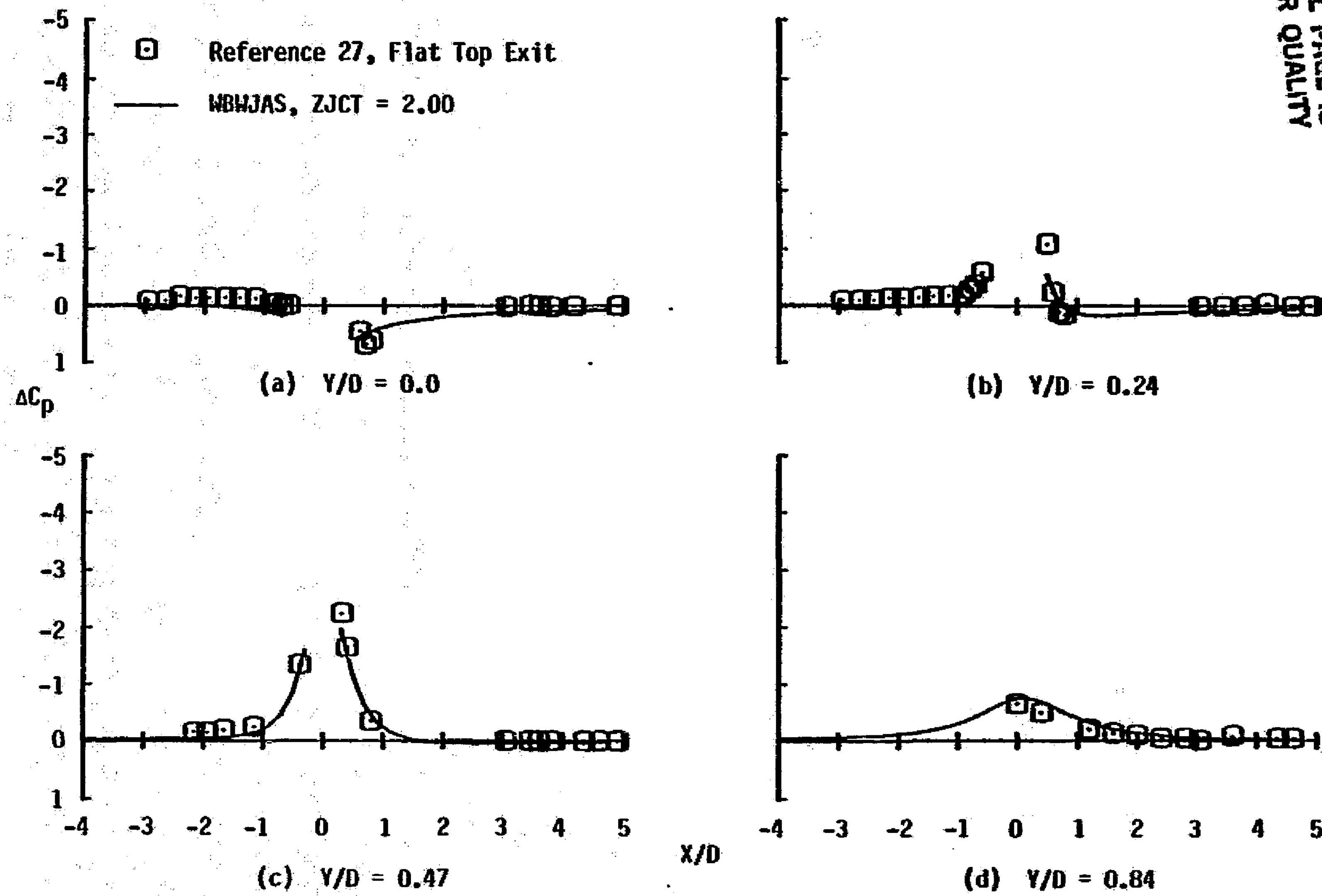


Figure 11. - Interference Surface Pressure (ΔC_p), Body of Revolution, R = 8.

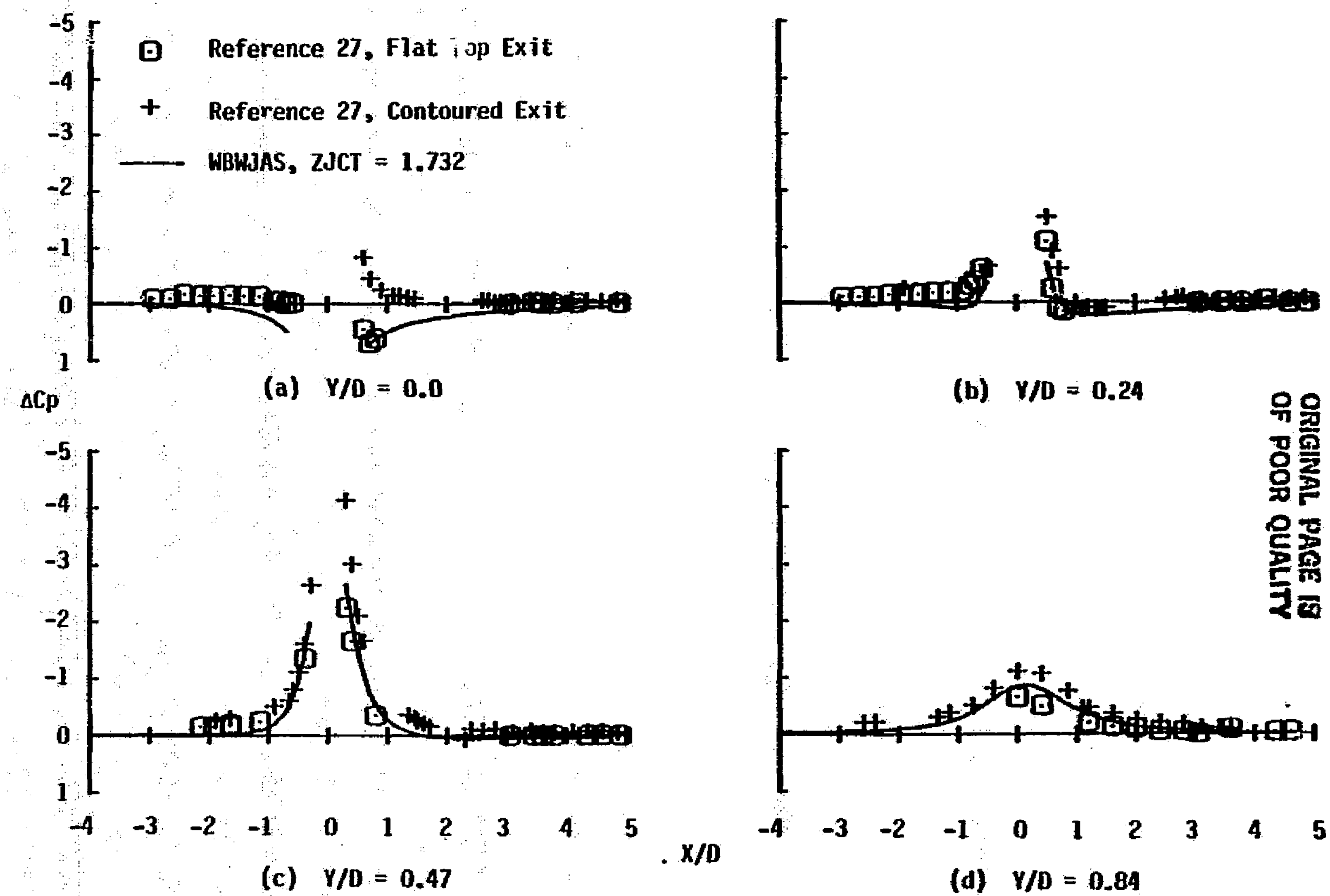


Figure 12. - Interference Surface Pressure (ΔC_p), Body of Revolution, R = 8.

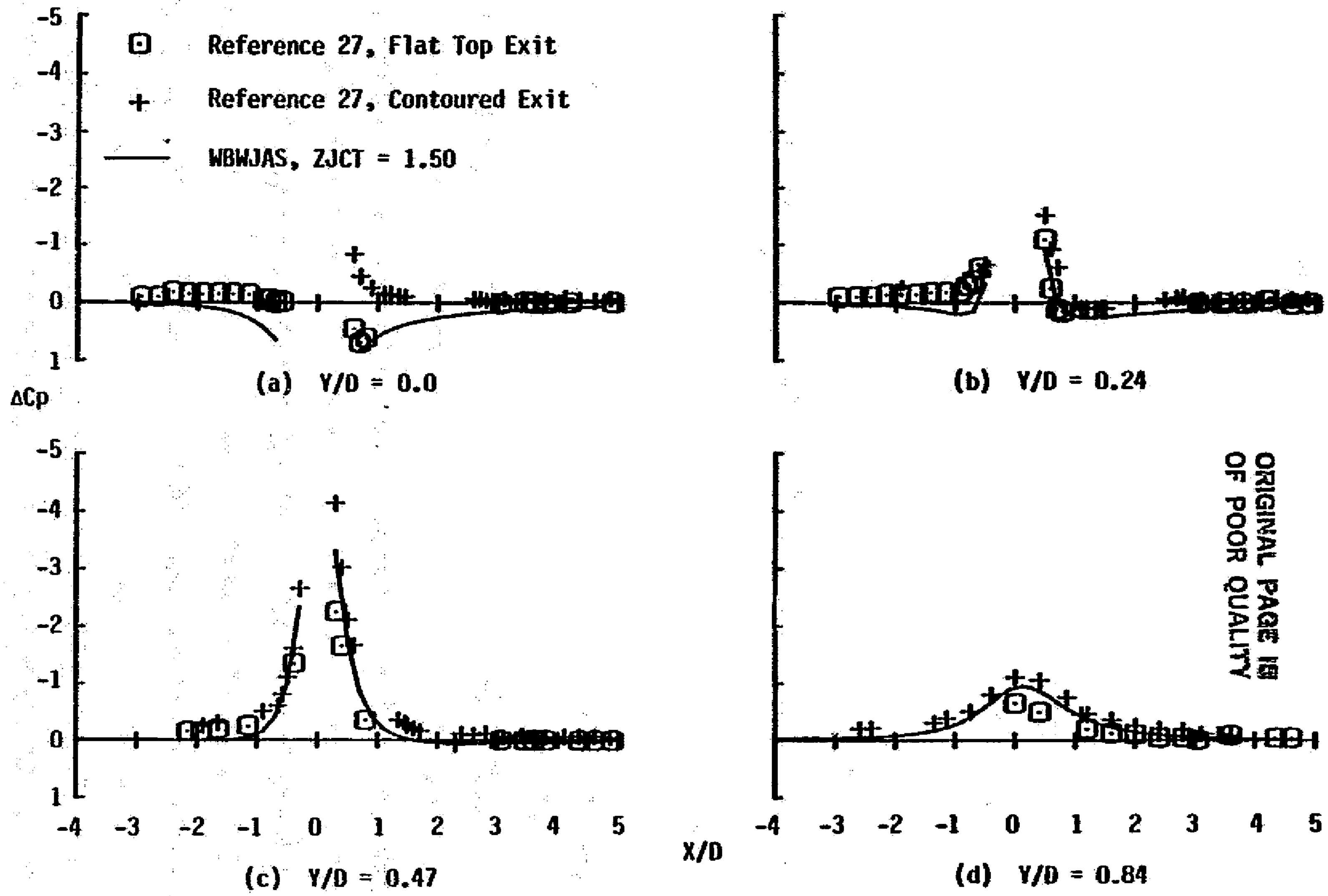


Figure 13. - Interference Surface Pressure (ΔC_p), Body of Revolution, R = 8.

jet exit. The value of ZJCT = 1.732 is chosen because the experimental model has jet side walls to a height of 1.732 inches above the body centerline. The ZJCT = 1.50 value is chosen to investigate any trends that may develop by submerging the jet within the body. The pressure plots in Figures 12 and 13 show that the WBWJAS data matches closely the experimental data for a contoured jet exit on all but the symmetry plane axial cut. The WBWJAS program does not predict the negative pressure field to the aft of the jet along the Y/D = 0.0 axial cut. The program shows a deceleration of the flow forward of the jet orifice and an acceleration region away from the jet orifice, downstream of the jet. The experimental data, on the other hand, shows no deceleration of the flow forward of the jet, and a definite low pressure region aft of the jet, i.e., a small wake region. The data of Figure 13, for ZJCT = 1.50, indicates that as the jet is submerged into the body, the computer code does not predict the low pressure region aft of the jet, along the Y/D = 0.0 cut. The submerging of the jet-in-crossflow exit does slightly improve the data for off centerline cuts (Y/D ≠ 0.0), when modeling the contoured exit jet.

Figure 14, which presents data for the contoured jet exit with the velocity ratio equal to 4.7, shows similar trends to the R = 8 contoured jet exit configuration. This indicates that discrepancies between the experimental and computer generated data are independent of jet-to-crossflow velocity ratio.

A wake correction is not used on the body-of-revolution models. Close agreement between the experiment and computer generated data for all axial cuts except the contoured exit symmetry plane axial cut indicates a wake correction is not necessary. This author believes the

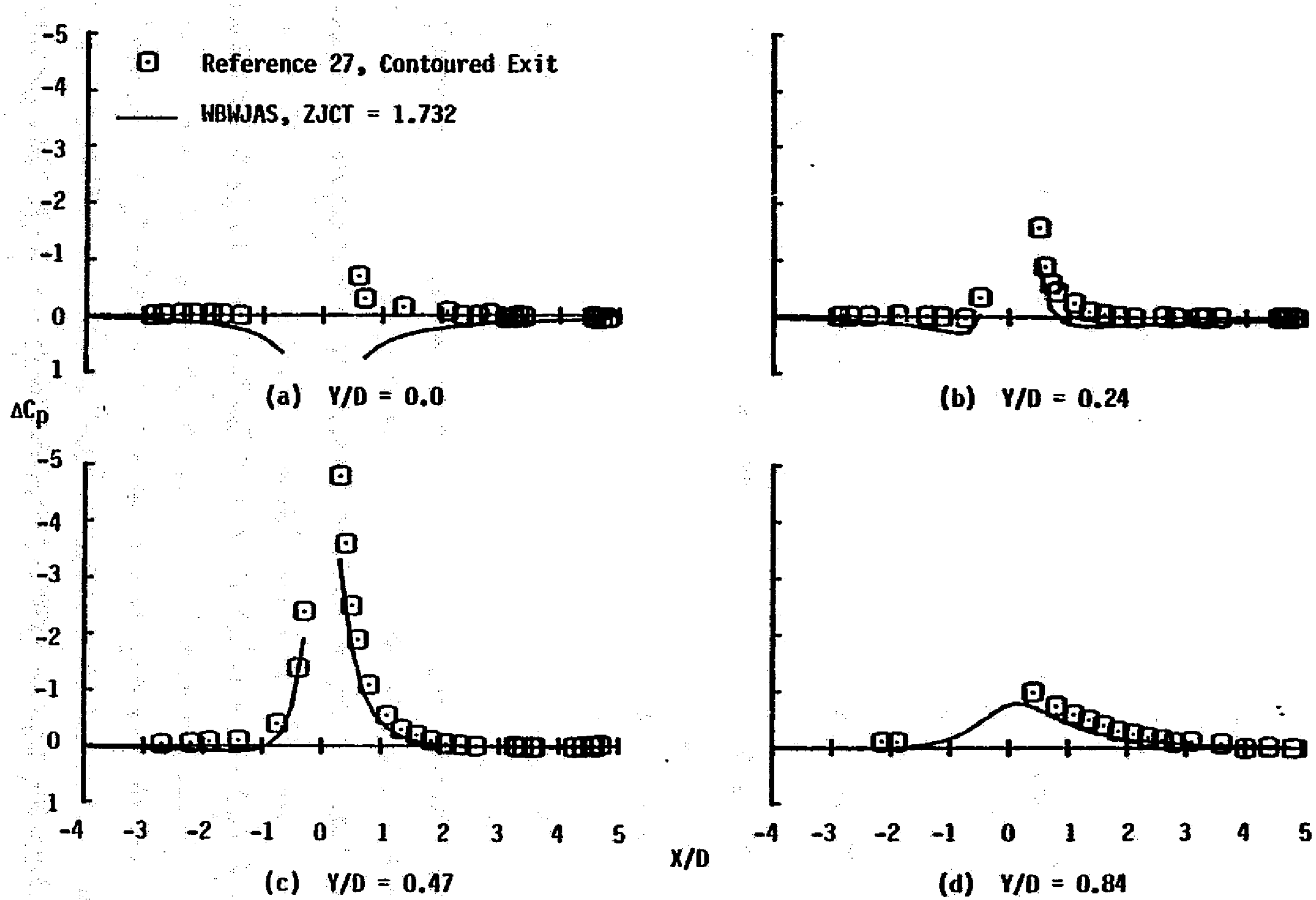


Figure 14. - Interference Surface Pressure (ΔC_p), Body of Revolution, R = 4.7.

absence of an extensive wake region aft of the jet in a crossflow is a result of surface flow around the body into the region aft of the jet orifice. This surface flow is possible due to the high degree of body curvature which results in little actual body surface area within the region aft of the jet orifice.

Force and Moment Data

The interference lift and pitching moment data for the body-of-revolution models is presented in Table 1. The interference lift and pitching moment are defined the same as for the flat plate configurations. Wind tunnel experimental data is not available for the body-of-revolution configurations.

The interference lift data shows a lift loss due to interference effects, which is to be expected. The steady increase of the lift loss is also expected from the submerging of the jet into the body, or the reduction of the jet-to-crossflow velocity ratio. The nose-up pitching moment is expected, although the trend of decreasing nose-up pitching moment with jet submersion into the body is not expected. Based on pitching moment changes for flat plate configurations, one would expect that as the interference lift loss increases, so would the interference pitching moment, although for this case, the majority of the lift loss is not aft of the jet. The increase in interference pitching moment is expected for the fourth case (BR 4), relative to the second (BR 2).

Symmetrical Wing Section

A symmetrical wing section model is used to investigate the accuracy of the jet/flat plate model where simulating a jet/wing configuration. The symmetrical wing section model used, as described earlier, is a NACA 0021 wing section with a fifteen unit chord and an

aspect ratio of twenty. The surface pressure data is presented with a wake correction which is similar to the flat plate wake correction. Six configurations are tested; a base configuration and five others which are each a single parameter perturbation of the base configuration.

The wing section modeled by the computer program is a three-dimensional semi-span wing, whereas the experimental model is a two-dimensional full-span wing. In order to compare the two sets of data, it is necessary to adjust the computer model's span such that three-dimensional (tip) effects within the region of interest are negligible. The tip effects are found to be insignificant, within the region of interest, by adjusting the full-span aspect ratio to twenty. This places the wing tip one hundred jet diameters from the jet orifice; the region of interest for interference pressure plots extends to eleven jet diameters from the jet orifice.

Six different wing configurations are modeled with WBWJAS. The wing configuration parameters which are varied are the following: the jet exit location in percent chord, X_j/c; jet diameter in percent chord, D_j/c; jet to crossflow velocity ratio, R; and the wing angle of attack, α. The base configuration has the following parameter values: X_j/c = 45%; D_j/c = 10%; R = 8; α = 0.0°. Changes are made to the base configuration as follows: X_j/c to 25% and 65%; D_j/c to 20%; R to 4; and α to 6°. The data obtained from each computer configuration is compared with experimental data and presented as surface pressure plots and force and moment data.

Surface Pressure Data

Data from each configuration is presented in the form of an interference surface pressure (ΔC_p) contour plot. Each graph is a co-plot of data from the WBWJAS computer program and experimental contour from wind tunnel tests.[26] The plots show the interference surface pressure coefficient contours on the lower surface of the wing. The pressure plots are given in Figures 15 through 20 with the base configuration shown in Figure 15. Each change to the base configuration involves only one parameter each and are shown as follows: Figure 16 is for $\alpha = 6°$; Figure 17 for the forward jet location, $X_j/c = 25\%$; Figure 18 the aft jet location, $X_j/c = 65\%$; Figure 19 is the lower value of jet-to-crossflow velocity ratio, $R = 4$; and Figure 20 is the large diameter jet, $D_j/c = 20\%$. Each ΔC_p contour line is labeled if space permits; if a line is not labeled its value is that of the closest neighboring contour line.

The following observations can be made about all of the contour plots: in the near jet region, less than two and a half jet diameters from the jet orifice, the interference surface pressures are predicted satisfactorily by the WBWJAS program; for the remainder of the region of interest the WBWJAS program is predicting stronger jet interference effects than those observed in the experimental data. The differences between the two sets of data might be attributed to the lack of lifting surface influence on the jet plume properties.

The effects of changing angle of attack to $\alpha = 6°$ do not appear to be strong. One should remember that the jet is on the wing lower surface. The effects may be more pronounced if the angle of attack had

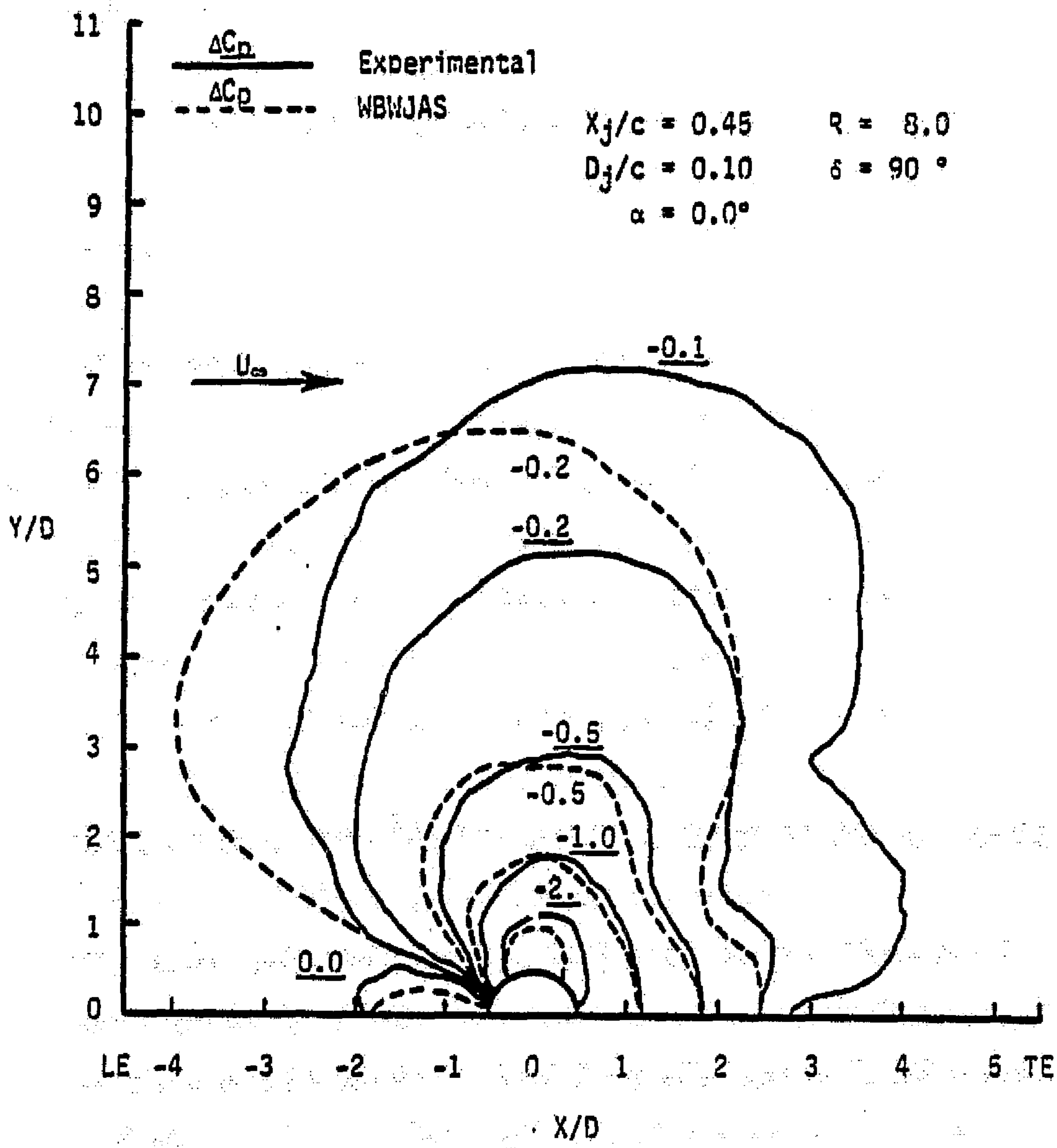


Figure 15. - Interference Surface Pressure Contours, Symmetrical Wing, Base Configuration.

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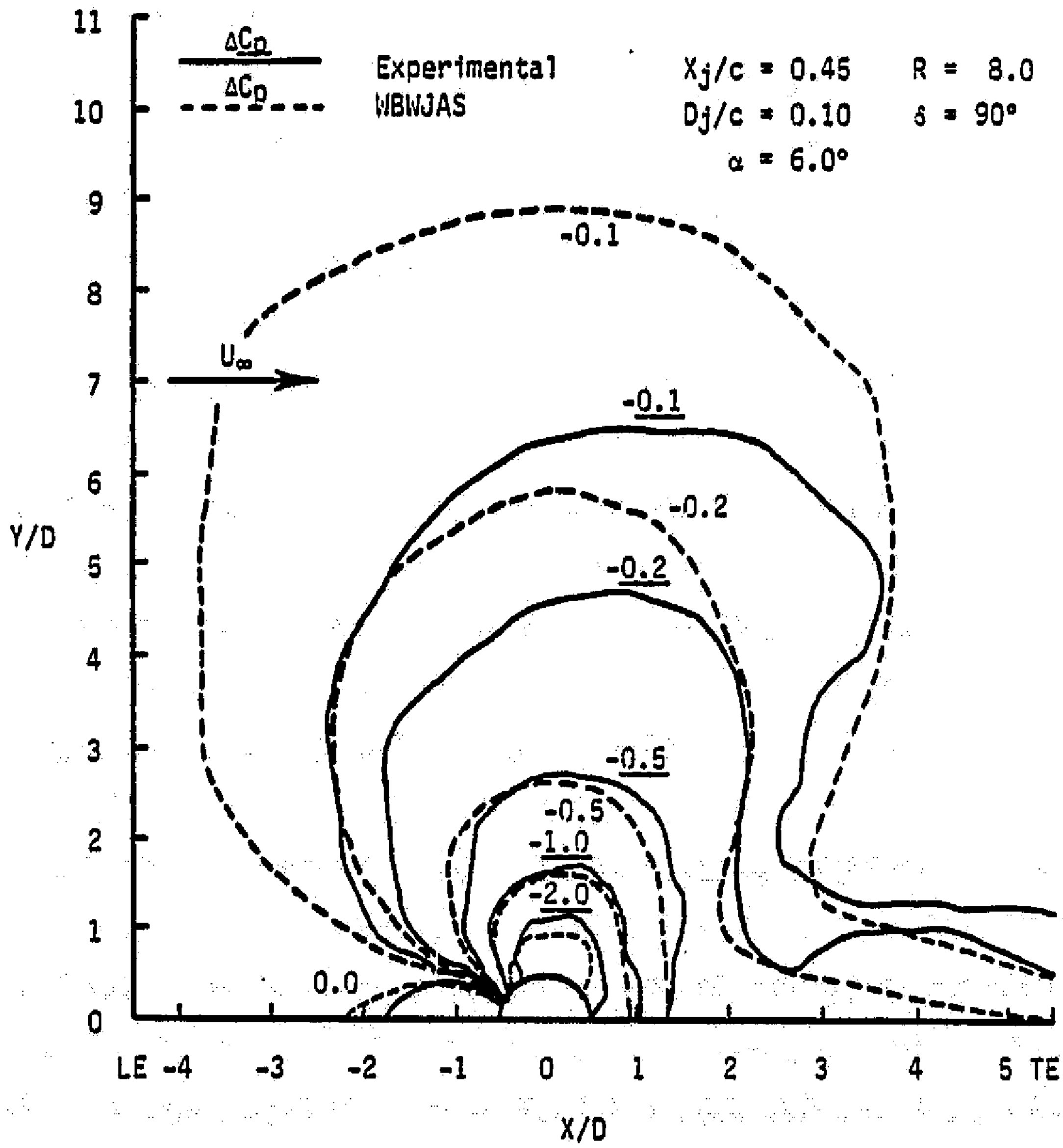

Figure 16. - Interference Surface Pressure Contours, Symmetrical Wing, Increase in α.

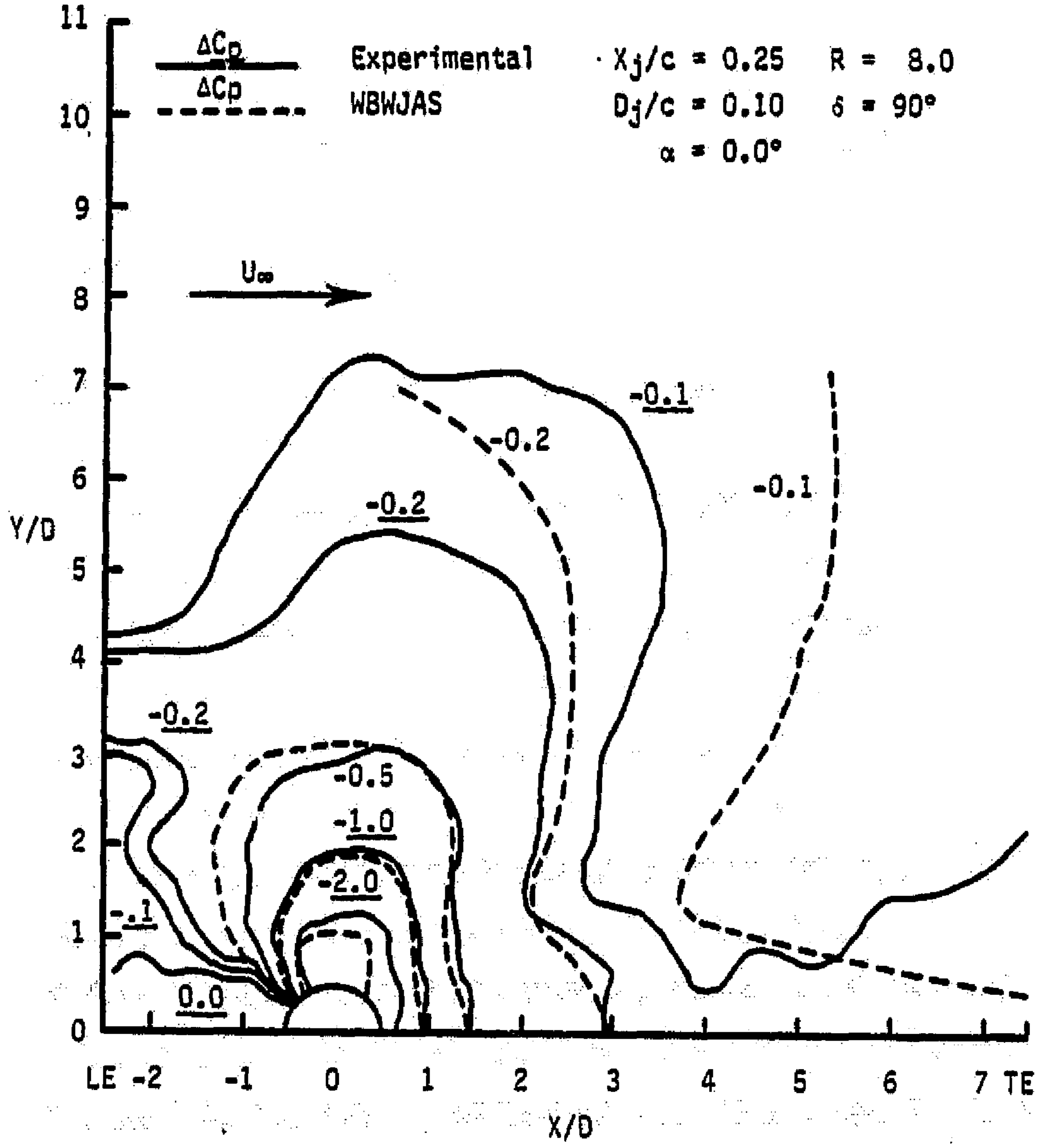

Figure 17. - Interference Surface Pressure Contours, Symmetrical Wing, Decrease in X_j/c.

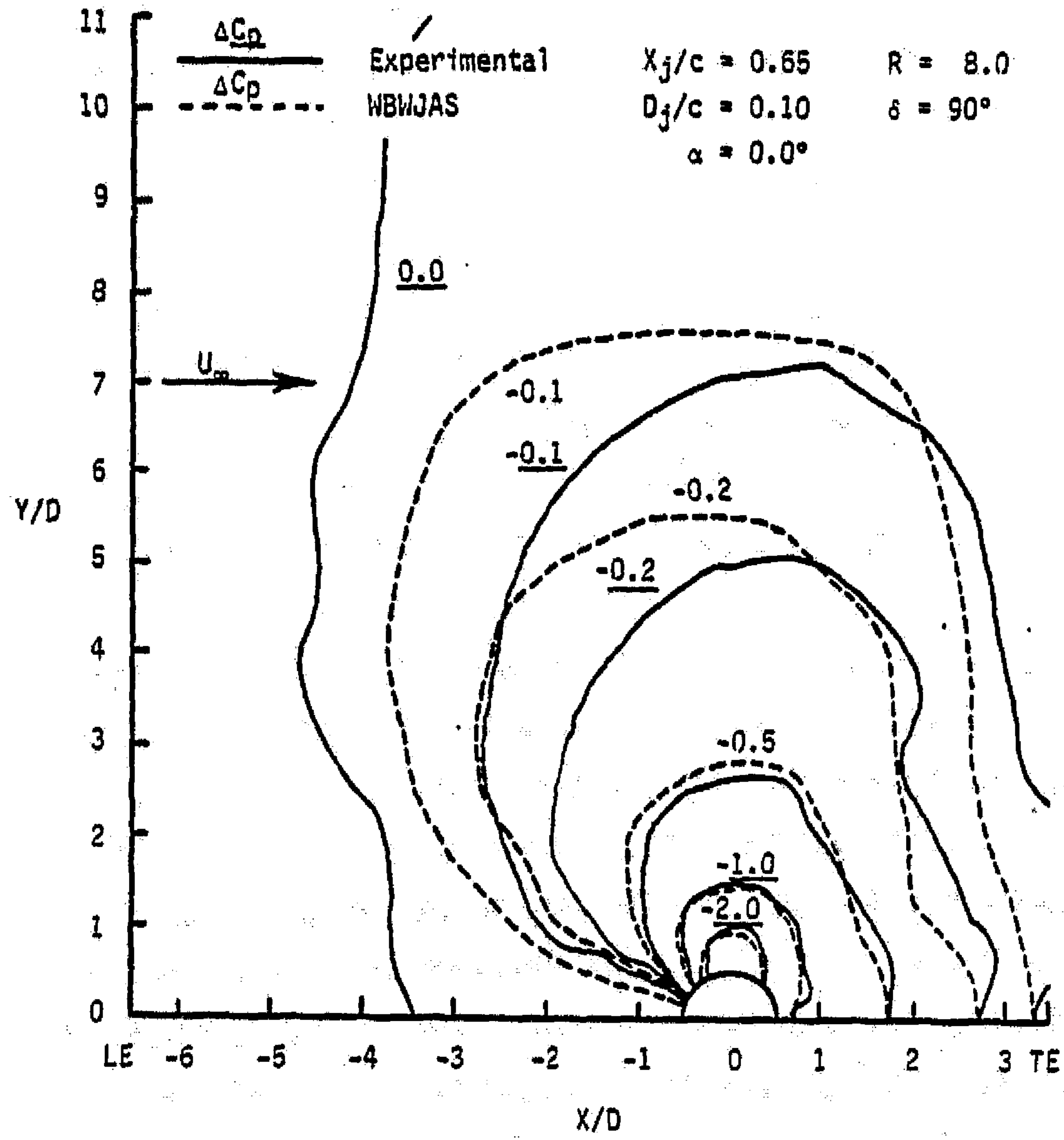

Figure 18. - Interference Surface Pressure Contours, Symmetrical Wing, Increase in X_j/c.

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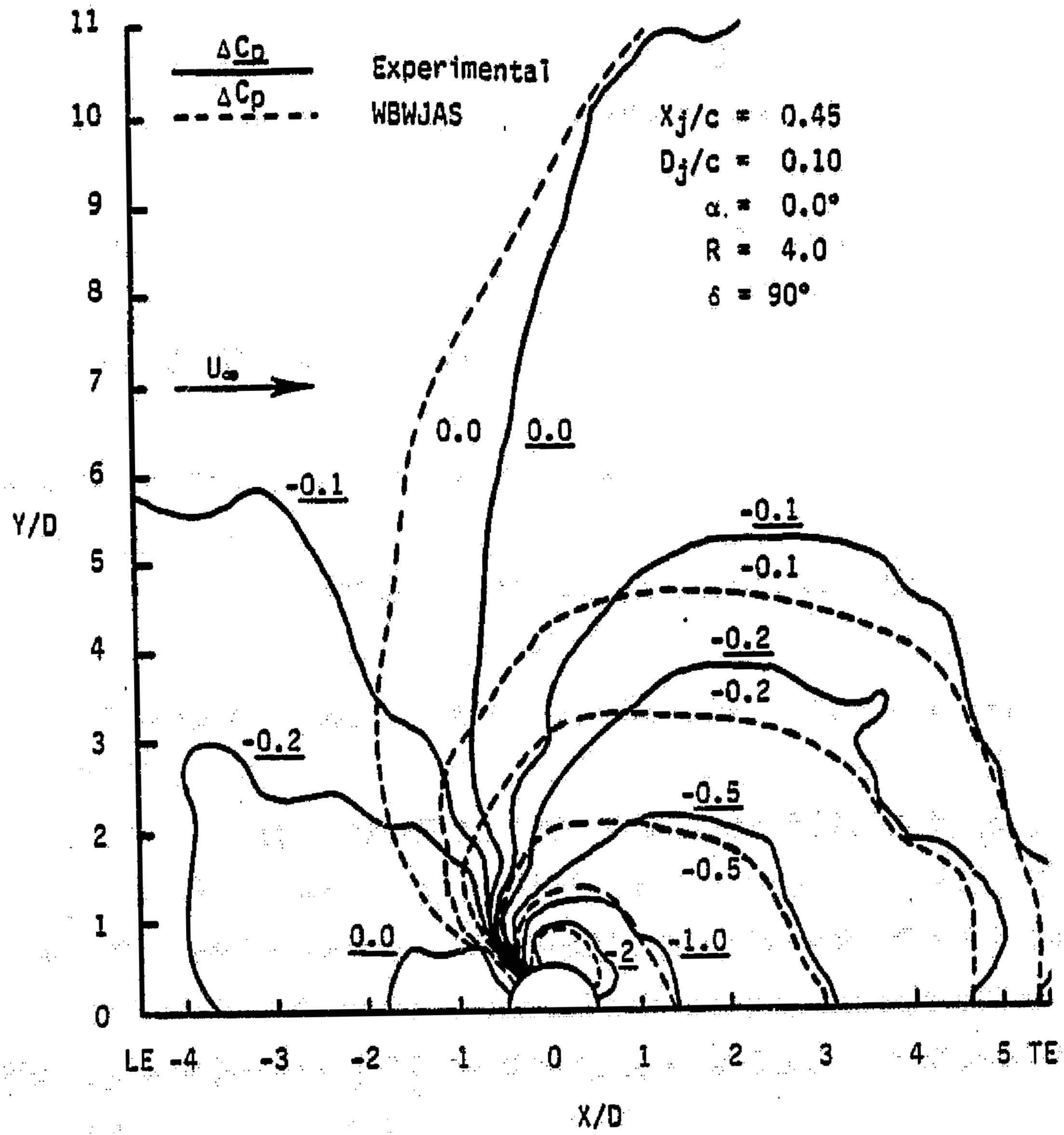

Figure 19. - Interference Surface Pressure Contours, Symmetrical Wing, Decrease in R.

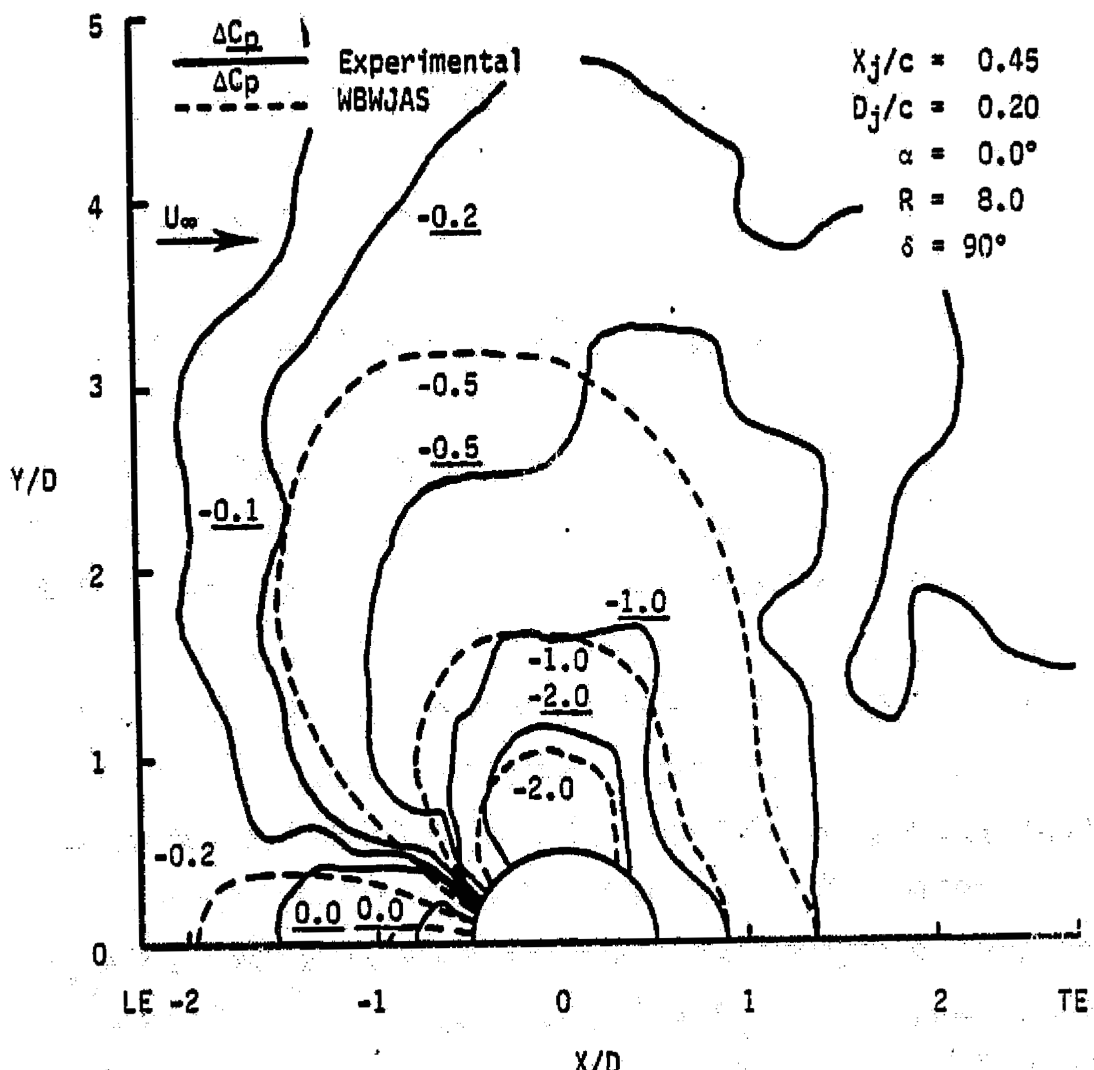

Figure 20. - Interference Surface Pressure Contours, Symmetrical Wing, Increase in Dj/c.

been changed to $\alpha = -6°$. Experimental data is only available for positive angles of attack.

The effects of jet movement fore and aft on the wing can be seen in Figures 17 and 18. Moving the jet forward on the wing tends to magnify the disagreement in the two sets of data. Moving the jet aft on the wing tends to decrease any disagreement in the two sets of data. These two observations may be due to the greater lifting surface effects near the leading edge of the wing.

The effects of decreasing jet-to-crossflow velocity ratio (R) are seen in Figure 19. This decrease in velocity ratio is similar to stronger lifting surface influences. Again the lack of lifting surface influence on the jet in crossflow may cause the computer model to predict stronger jet-in-crossflow interference effects.

The effect of increasing jet diameter, as shown in Figure 20, appears only to magnify the results for the base configuration. The jagged appearance of the experimental data contour lines may be due to sparse data. It has been this author's experience that sparse data often lead to inaccurate contour lines.

Force and Moment Data

Interference lift and pitching moment data are not presented here for the symmetrical wing. The reader is reminded that the force and moment data from WBWJAS is only available without a wake correction, therefore, it is not representative of the real flow field. The author of reference 26 indicated that he encountered balance problems during the wind tunnel tests, thus the experimental data is not reproduced here.

General Conclusions

Results from the configurations tested show the jet/aerodynamic-surface model, as presented here, is capable of approximating the adverse aerodynamic interference effects associated with some generic aerodynamic configurations in transitional flight. The results of the flat plate models indicate that the jet/aerodynamic-surface model presented here is correctly approximating the surface pressure distribution on a flat plate model when a wake correction is used in the viscous wake region. The body-of-revolution model demonstrates that a wake correction is not always necessary, and that the jet interference effects on this body are similar to those on the flat plate model. The surface pressure data from the symmetrical airfoil models indicate the lifting surface effects on the jet in crossflow are not detrimental to this jet/aerodynamic-surface model. These favorable results should provide the necessary justification to continue development on the iterative method proposed.

Continued Research

As a close to this report the author would like to suggest the following areas for research and development on the WBWJAS program: development of a wake model which manipulates the jet perturbation velocities in the wake region; extension of the jet-in-crossflow model to handle varying jet injection angles; extensions to handle various jet exit velocity profiles and shapes; increases in the range of valid jet-to-crossflow velocity ratios; and most important, to make the program iterative for the effects of lifting surfaces.

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